QoS-Aware Routing in Future All-IP Access Networks

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I would like to dedicate this thesis to Rana,

the light of my universe...

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Never planning before to get here, until the opportunity came, I cannot express my happiness in words for one of the most worthwhile experiences in my life. While tackling the problems during a PhD, one may learn invariable lessons: from self-adjustment to facing the failures; from bitterness of being on the verge of hopelessness, to the beauty of getting the confidence and inclination to question all that is around, and seek out new ways of doing it. Most importantly, the lesson of learning to push yourself out of comfort zone to make progress. Without a doubt, I would not be able to sit and write this acknowledgement today without many people throughout my life, whose presence and true friendship in times of need have shed the light of beauty into my life.

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Abstract

The proliferation of mobile devices over the past several years has created a whole new world of the Internet. The deluge of applications for every aspect of today's life has raised the expectation of having ubiquitous connectivity, with a desired Quality of Service (QoS). Although appealing, it has violated the original Internet design which was not intended to support mobility, neither better than best-effort delivery.

It is also a well-known fact that technology is an ever-advancing need of the human society, and undeniably the Internet forms a major part of our lives now. Everyday more and more users flood the Internet with enormous amount of data and information. As such there is a need to effectively handle all the information and traffic in a way that there is an availability of high speed network routing without any loss in data transmission.

QoS provisioning has been one of the long lasting focuses in the network research community. While designed for fixed networks, the use of QoS protocols in IP-based mobile networks, where hosts dynamically change their point of attachments, imposes new challenges to be studied and analysed. Furthermore, a massive growth in the access network traffic with its highly unpredictable nature can cause bottlenecks in some links while others are under-utilised, rendering the load skewed, and therefore, breaching the QoS provisioning commitments.

The main objective of this research is to propose a novel QoS mechanism for mobile networks. The new scheme is composed of two different approaches accountable for QoS provisioning in next-generation access networks. Firstly, a new method is proposed that minimises the signalling overhead, as well as the interruption in QoS at the time of handover. Through a developed analytical framework and simulation scenario, the performance of the new scheme is investigated thoroughly, with the focus on the figures of merit that affect the efficiency of using QoS signalling protocols in access networks.

Secondly, a new QoS-aware routing mechanism is proposed, based on the OSPF protocol, intending to minimise the congestion on the links while at the same time complying with traffic requirements. OSPF was created for providing flexibility and great scalability, and although widely used today, does not allow arbitrary splitting of traffic.
This research delves into the study and development of IP-based networking, built upon an extension to OSPF routing protocol, that will foster integrated functioning of technologies that currently lead the vision for the novel telecommunication infrastructures and service provision. This novel QoS-aware approach, Multi-Plane Routing (MPR), is applied in the context of access networks for IP routing. MPR divides the physical network into several logical routing planes, each being associated with a dedicated link weight configuration. Network topology and node degree distribution directly impact the performance of our strategy.

The foundation of this research's vision for networking in future networks is in the evolution and derivatives of IP routing that are inherited from the native Internet and stand as the solution for networking in the sought "all-IP" integrated modern telecommunications infrastructures. MPR is proposed to offer a traffic engineering solution for future all-IP access networks that uses

QoS-awareness and policies for plane selection to maximise path diversity, increase overall throughput and satisfy QoS requirements for sessions.

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List of Abbreviations

AN	Access Network
AR	Access Router
AS	Autonomous System
ASBR	AS Border Router
ATM	Asynchronous Transmit Mode
BA	Binding Acknowledgement
BGP	Border Gateway Protocol
BS	Base Station
BU	Binding Update
CBR	Constraint-based Routing
CN	Correspondent Node
CoA	Care of Address
DiffServ	Differentiated Services
DSCP	DiffServ Code Point

ECMP	Equal Cost Multipath
GW	Access Gateway
HA	Home Agent
HIP	Host Identity Protocol
HoA	Home Address
IETF	Internet Engineering Task Force
IGP	Interior Gateway Protocol
INP	Internet Network Provider
IntServ	Integrated Services
IP	Internet Protocol
IS-IS	Intermediate System to Intermediate System
ISP	Internet Service Providers
LCoA	Local Care of Address
LMA	Local Mobility Agent
LMA	Local Mobility Anchor
LSP	Label Switched Path
LTE	Long-Term Evolution
MAG	Mobility Access Gateway
MA	Mobility Agent
MAP	Mobility Anchor Point

MDE	Monitoring Decision-making Execution
MLD	Maximum Link Delay
MLU	Maximum Link Utilisation
MN	Mobile Node
MPLS	Multi-Protocol Label Switching
MPR	Multi-Plane Routing
MT-OSPF	Multi-Topology OSPF
OSPF	Open Shortest Path First
PALU	Proactive Autonomic Load Uniformisation
PBA	Proxy Binding Acknowledgement
PBU	Proxy Binding Update
PHB	Per-Hop Behaviour
PMIPv6	Proxy Mobile IPv6
Q-MPR	QoS-aware Multi-Plane Routing
QoS	Quality of Service
RCoA	Regional Care of Address
RPC	Resource Provisioning Cycle
RP	Routing Plane
SDN	Software-Defined Networking
SLR	Service Level Requirement

SLS	Service Level Specification
TE	Traffic Engineering
TM	Traffic Matrix
TSpec	Traffic Specification
UDN	Ultra-Dense Network
WiMAX	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

Of all the major inventions of the twenty-first century, without a doubt, the Internet is one of the greatest inventions of all time. The widespread use of the Internet technologies has created a wave of innovations, resulting in a profound impact on human lives. Over the last decades the Internet has grown tremendously and has penetrated all aspects of everyday life, so much so that life without it would be unimaginable, at least for young people if not for all. The successful widespread adoption of the Internet has acted as a driver behind the growth of applications, from the release of the world wide web and email in 90s to a deluge of applications for different parts of today's life. With the uncontrollable increase of mobile devices and the popularity of smart phones, a second revolution of Internet has started to emerge. Even more massive than the first one, the second involves the integration of the virtual and physical worlds almost everywhere all the time. With six of the world's seven billion people have mobile phones [1], it has become the first screen of choice among many of its users, for entertainment, communication, comment, interaction, gaming and socialising. What is certain is that success cannot be achieved unless the quality of service meets the users' expectations. Bandwidth is one of the most critical resources in the Internet. It used to be very scarce in the early stage of the Internet. Although the absolute volume of bandwidth in today's Internet has increased dramatically, the demands have increased even faster, because people tend to put more and more sophisticated types of information onto the Internet. For example, after the emergence of the World Wide Web, multimedia applications – including audio and video – account for a large portion of today's traffic. People are now using on a daily basis real-time High Definition TV (HDTV) services over the Internet. Therefore, bandwidth is always a resource that needs to be managed carefully. Previously the backbones were the focus; and nowadays the access networks are. Besides the bandwidth metric, some other Quality of Service (QoS) requirements, such as delay, jitter and packet loss, are also becoming more and more important for such new applications. Also, the Internet owes its success to its naive operation, treating all packets with different characteristics (e.g., voice, video, data) the same. This one-size-fits-all service design principle, although being robust enough to stand the huge expansion, cannot live up with today's demands anymore. Therefore, the need to migrate from the best-effort service model to one, in which service differentiation can be provided, seems inevitable for future network architectures. This challenging issue has inspired a large body of research over the last few years.

1.1 Toward all-IP Access Networks

With the fast adoption of IP-based communications for mobile computing, users are expecting a similar service in wireless and wired networks. This raises the need for setting guarantees to the QoS offered service regardless of the access network technology or the mobility of terminals. The telecom world is moving towards an 'all-IP' network, as IP is the dominant internetworking protocol in operation today. It becomes more and more recognised that using IP as the underlying infrastructure for next generation Access Networks (AN) makes strong economic sense and technical sense, both in installation and in operation, since it takes advantage of the ubiquitous installed IP infrastructure [2]. In light of these new expectations, research has raised questions on multipath diversity [3] in IP networks and naturally reassesses the shortest-path routing paradigm for the needs of the future networks. Perhaps these very needs have caused a discrepancy in deployment of all-IP networking including IP routing protocols all the way down to the edges of networks, that is, wireless access points in access networks. And from an IP development and deployment perspective, definition of access networks is rather unfounded. While cellular networks deliver IP services, telecom access networks run additional network layer routing solutions for fulfilling the needs of service deliveries while prudently nudging IP integration in their evolution. On the other hand, IP development has envisaged IP access networks for wireless terminals founded on IP routing in the network layer [4] and providing seamless mobility to the terminals [5]. Whether physically [4] or logically [6], IP access networks can be generally defined as the IP routing transit space in an administratively scoped network environment, bounded by the edges: gateway, providing connection to the Internet, and, access router, providing access to terminals. It is easy to imagine the opportunities for flexible deployment of IP access networks via rollouts and networking of wireless access points with technologies such as WiFi, femtocells and macrocells solutions.

1.2 Big Picture: QoS Routing and Traffic Engineering in the Internet

Networks fall into two major categories in terms of routing paradigms they are using: connection-oriented networks (also called flow-based networks) and hop-by-hop networks. Examples of connection-oriented networks include the Asynchronous Transmit Mode (ATM) networks and the Multi-Protocol Label Switching (MPLS) networks. They do routing and traffic engineering based on connections (flows) by using, for example, virtual paths. QoS routing and traffic engineering goals are normally achieved by finding optimal or near-optimal explicit routing algorithms (sometime under multiple constraints) [7]. A good survey of flow-based QoS routing is presented in [8]. On the other hand, the hop-by-hop routing paradigm forms the basis of today's Internet, just because it is simple, reliable, and has a wide-spread deployment. In fact, the most commonly used protocols, both intra-domain and inter-domain, are basically hop-by-hop. Some examples are the Open Shortest Path First (OSPF) protocol [9] or IS-IS protocol [10] for intra-domain routing and the Border Gateway Protocol (BGP) [11] for inter-domain routing. Some basics of hop-by- hop networks will be given in the next chapter. QoS routing and traffic engineering in hop-by-hop networks normally use the Dijkstra's algorithm (or more precisely, the Dijkstra-based algorithms) by manipulating the ways of setting link weights and finding shortest paths with respect to the link weights [12–15]. In our research, we focus only on intra-domain routing and traffic engineering issues in access networks.

1.3 Key Challenges

The original design of the Internet Protocol (IP), as the single common communication protocol of the Internet, does not support a better than best-effort service. Neither does it support mobility. Each of these two issues has been adequately, though separately, addressed by multiple approaches in different categories. Today, most access networks opt to deploy Cisco's MPLS, which enables enterprises and service providers to build networks that deliver services over a single infrastructure. MPLS is a flow-based packet routing mechanism that assigns streams of packets to Label Switched Paths (LSPs). The most distinctive advantage of MPLS resides in its capability of arbitrary routing and splitting traffic and it is this advantage of MPLS that makes it a more convincing solution for requirements posed in access networks, something that IP routing protocols fall short off. Yet, although effectively running as a supplementary routing solution in IP packet forwarding, MPLS often relies on IP routing protocols (such as OSPF intra-domain routing protocol) for computing LSP paths in networks. We also note some shortcomings of MPLS, mainly, its scalability and robustness issues as flows are mapped to dedicated LSPs. The overhead of building LSPs can be very high in relatively large-size networks due to large size of routing table and state information [16]; MPLS introduces extra complexity of calculating, setting up and maintaining LSPs between every source-destination pair. Traffic load balancing in a network is crucial to both the overall network performance (from the network operator's point of view) and the applications that use the network (from the user's point of view), especially for hop-by-hop networks, because this type of networks is prone to incur congestion if bandwidth is not managed carefully [17]. Our approach is based on OSPF routing protocol, the most widely used intra-domain routing protocol nowadays in backbone networks, large enterprise and data centers.

OSPF is directly operating over IP and is an adaptive link-state protocol, i.e. each router within the network has a complete view of the network state and topology. Furthermore, OSPF is robust against element failures (e.g. node or link), flexible and scalable. However, OSPF does not allow arbitrary traffic splitting nor efficient path diversity as path alterations can be timely requiring changing of link weights and retransmitting the changes across the network.

1.4 Contributions of the Thesis

The contributions of my work in this thesis, leading to the design of a novel QoS for access networks is two-fold: first the work proposes an efficient QoS-aware routing strategy for access networks with both an offline (network planning phase) and online (network operating phase) mechanisms with per-flow resource reservation. Second, a new QoS mobility support mechanism taking into account the possible approaches for mobility management and per-flow resource reservation. To that end, the breakdown of the contributions can be listed as follows:

- The proposal for a new link-state edge-based traffic engineering mechanism, Multi-Plane Routing (MPR), in access networks is discussed in Chapter 3, and will be part of the network planning stage. Our approach is based on Multi-Topology OSPF (MT-OSPF) [18] and its architecture will be elaborated in details. This new method provides a simple, efficient, and practical solution to achieve traffic load balancing in access networks. It pushes traffic splitting to the network edge and keeps the network core simple. It complies with existing protocols and therefore it is easy to deploy. The results obtained show not only that the scheme reduces the average link utilisation (as well as the maximum link utilisation in the network), but also the average link delay.

- The method is then enhanced by introducing QoS awareness, Q-MPR, in accordance with the Service Level Requirements (SLR) of traffic flows. This approach is beneficial and desirable to TCP flows, because flow boundaries are easy to enforce using this method, so that the "out-of-order delivery" problem is eliminated. The model shows very promising improvements on network performance in terms of packet delay and jitter, blocking probability and link load.

- The proposal for our mobility support mechanism in Proxy Mobile IPv6 (PMIPv6) [5] networks is presented in Chapter 5. The analytical model for load balancing in PMIPv6 networks based on optimal Local Mobility Agent (LMA) selection is described in details. The results indicate a net reduction in overall LMA utilisation and TCP window size.

- An analytical framework, alongside the network level simulation scenario in Network Simulator 2 (NS-2), is developed to investigate the performance of the new scheme in access networks, taking into account both traffic behaviours and mobility management.

1.5 Thesis Outline

The rest of the thesis is organised as follows: Chapter 2 introduces some background information on hop-by-hop networks, traffic engineering in OSPF networks, and the rationale behind a move toward full IP-based high path diversity access networks where good and applicable traffic engineering solutions are, to date, lacking. Chapter 3 elaborates on the main contribution of the thesis with the novel Multi-Plane Routing mechanism for access networks. Chapter 4 focuses on the extension to this mechanism by introducing QoS awareness that will . Chapter 5 describes our load balancing technique with mobility support in mobile networks. Chapter 6 concludes this dissertation and points out future work for tackling the limitations of the thesis and research directions. Finally, we provide some detailed information of the extension module to NS-2 network simulator to enable the full use of Multi-Plane Routing in Appendix B.

Chapter 2

Background Study

The Internet does not support a better than best-effort service. By emerging new facets of the applicability of the Internet on users' daily lives, a quality of service provision has become a stringent demand for ever-increasing bandwidth starved applications, and therefore, an issue of great interest within the research community. The proliferation of Internet-connected mobile users with distinct requirements, not only drives up the demands for seamless connectivity, it raises the expectations of service quality for the video-dominant mobile data traffic. Since hop-by-hop networks are the basic network environment that this dissertation will focus on, it is necessary to introduce some fundamentals of this type of network in this Chapter. Next, some traffic engineering principles and latest research work will be presented for OSPF networks. The Chapter will then move on to providing a rationale as to why next generation networks need path diversity. This chapter will continue by giving an overview of the major quality of service protocols standardised by Internet Engineering Task Force (IETF). Finally, Section 2.5 exposes the main concepts of Mobile IP.

2.1 What Is Hop-By-Hop Routing?

Hop-by-hop routing is the basic routing paradigm in today's Internet. It is routing-table-driven and destination-address-based. This means, first, each node (router) in such a network constructs its routing table independently using its own topology information of the entire network; second, each node looks up the next hops in its routing table for incoming packets based on their destination addresses. No flow information or source address information is used while forwarding. The routing table is a data structure used at each node in a hop-by-hop network. It serves as a lookup table that takes destination IP addresses as lookup keys and returns next hops accordingly. Basically, a routing table stores entries of (destination address, next hop) pairs. When an IP packet arrives at a node, the node first looks into the packet's IP header to find its destination address. Then the node uses the destination address as a key to consult its routing table. If an entry matches the destination address, the corresponding next hop is used to forward the packet. Otherwise, the packet is forwarded to a default next hop. Traditionally, destination addresses are the only information that is used to consult the routing table. However, some extra information in IP headers may also be used, such as the ToS/DSCP bits [19–21].

Figure 2.1 shows an example of hop-by-hop routing where the hop-count shortest path scheme is used. Let us consider only one destination, say, Node 5. The routing tables in the figure shows entries associated with Node 5 only. Other entries are omitted. As we can see, because hop-count shortest path scheme is used, Node 1 chooses the path $\langle 1 \rightarrow 2 \rightarrow 4 \rightarrow 5 \rangle$ to reach the destination Node 5. Therefore, it uses Node 2 as its next hop to reach Node 5 and keeps this next hop information in its routing table, as shown in the figure. If an IP packet arrives at Node 1, and if its destination address is Node 5, then

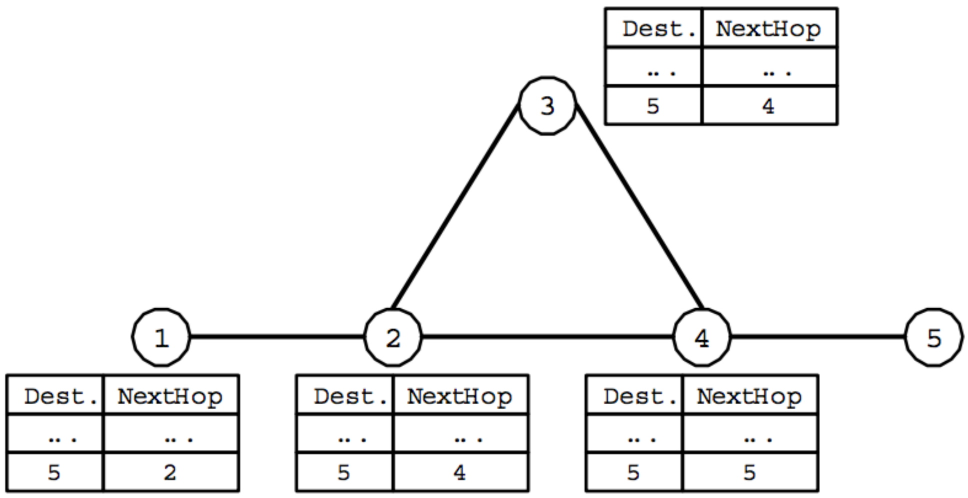


Fig. 2.1 Example of hop-by-hop routing: hop-count shortest path scheme is used.

Node 1 will forward the packet to Node 2 accordingly. Similarly, Node 2 makes its own routing decision (using the hop-count shortest path scheme) and sets up its routing table. It uses Node 4 as its next hop to the destination, Node 5. Then the packet forwarded from Node 1 will be forwarded to Node 4. Finally, Node 4 will forward the packet to Node 5. Indeed, the routing and forwarding process in a hop-by-hop network works like a link list.

An important issue and challenge in a hop-by-hop network is the avoidance of forwarding loops. Since every node in a hop-by-hop network makes routing decisions and forwards packets independently, the routing algorithm should be consistent so that the forwarding loop-freedom is ensured. Most of the existing routing schemes are based on the shortest-path searching algorithms, such as Dijkstra's algorithm. As we can see in the above example shown in Figure 2.1, if hop counts are used as link weights, then the Dijkstra's algorithm can guarantee to be loop-free. But besides the hop count, different weight functions and parameters may be used to determine link weights in a network. This will be more detailed in the following section (Section 2.2).

2.2 Overview of Traffic Engineering Classifications

Traffic engineering (TE) is essential for today's Internet Service Providers (ISPs) because of rapid growth of the network and increasing demands coming from end users and new applications. The major task of traffic engineering is to find appropriate routing and traffic allocation schemes for given physical networks and user traffic demands, so that the traffic load is balanced and the overall network performance is optimised. In the thesis, we will focus solely on intra-domain traffic engineering. The task of intradomain TE is to optimise customer traffic routing between Autonomous System (AS) border routers (ASBRs) within a single domain.

One way to provide traffic engineering is to deploy new flow-based connection-oriented protocols, such as the MPLS protocol [22–24], where traffic engineering is easy to implement. However, the destination-based hop-by-hop routing protocol, such as the OSPF protocol [9], is still the most commonly used intra-domain routing protocol in today's Internet. On one hand, it is simple, robust, and highly scalable. But on the other hand, it is believed that OSPF could lead to congestion, hence suffering from bad performance if traffic engineering does not exist. Therefore, traffic engineering in OSPF networks is extremely important and meaningful, and a good traffic engineering solution on top of OSPF can both improve network performance and leverage the widespread deployment of the OSPF.

The following subsections (Subsections 2.2.1 to 2.2.3) will be dedicated to giving an overview of the different classes of traffic engineering employed today.

2.2.1 MPLS-based TE vs. IP-based TE

The concept of traffic engineering was actually first introduced in MPLS-based environments [23, 25]. By intelligently setting up dedicated LSPs for delivering encapsulated IP packets (e.g. using constraint-based routing[1]), MPLS-based TE can provide an efficient paradigm for traffic optimisation. The most distinct advantage of MPLS-based TE is its capability of explicit routing and arbitrary splitting of traffic, which is highly flexible for both routing and forwarding optimisation purposes. However, since traffic trunks are delivered through dedicated LSPs, scalability and robustness become issues in MPLS-based TE. First, the total number of LSPs (assuming full mesh or equivalent) within a domain is $O(N^2)$ where N is the number of ASBRs. This means that the overhead of setting up LSPs can be very high in large-size networks. In addition, path protection mechanisms (e.g. using backup paths) are necessary in MPLS-based TE, as otherwise traffic cannot be automatically delivered through alternative paths in case of any link/node failure in active LSPs.

The first IP-based TE solution was proposed by Fortz *et al.* [17, 26, 27]. The basic idea of their approach is to set the link weights of interior gateway protocols (IGPs) according to the given network topology and traffic demand so as to control intra-domain traffic and meet TE objectives. Unlike MPLS-based TE, which enables dedicated explicit routing for individual flows, such "fine-grained" path selection cannot be achieved in IP-based TE, as the changes of IGP link weight may affect the routing patterns of the entire set of traffic flows.

In comparison to the MPLS-based approach, these IP-based TE solutions lack flexibility in path selection, since explicit routing and uneven traffic splitting are not supported. However, the IP-based approach has better scalability and

[1]In constraint-based routing, all infeasible links (with unsufficient available bandwidth) are removed from the network toplogy

availability resilience than MPLS-based TE, because no overhead for dedicated LSPs is required, and also because traffic can be automatically delivered via alternative shortest paths in case of link failure without explicitly provisioning backup paths. However, given this type of auto-rerouting in the IP-based environment, link failures may introduce dramatic changes to traffic distribution (thus introducing new traffic congestion) even across multiple domains.

Table 2.1 summarises the key differences between MPLS-based and IP-based traffic engineering.

Table 2.1 MPLS/IP TE comparison

	MPLS-based TE	**IP-based TE**
Routing mechanism	Explicit routing with packet encapsulation	Plain IGP/BGP-based routing
Routing optimisation	Constraint-based routing (CBR)	IGP link weight adjustment, BGP route attribute adjustment
Multipath forwarding	Arbitrary traffic splitting	Even traffic splitting only
Hardware requirement	MPLS capable routers required	Conventional IP routers
Route selection flexibility	More flexible – arbitrary path	Less flexible – shortest path only
Scalability (overhead in maintaining network state)	Less scalable	More scalable, with scalability of underlying routing protocol
Failure impact on traffic delivery (availability)	High (normally need backup paths in case of failures)	Low
Failure impact on TE performance	Low	High

2.2.2 Offline TE vs. Online TE

The second part of our taxonomy is to classify TE as offline, which forms part of the network planning phase, and online which takes place during network operation. The principal difference between offline and online traffic engineering is the availability of a traffic matrix (TM) and timescale of traffic manipulation. The concept of a TM was originally associated with intra-domain TE, where ingress/egress points of traffic are fixed. In this case the overall traffic demand on the network can be represented by a matrix TM, say, with each element $t(i, j)$ of the TM being the total bandwidth demand of all individual traffic flows (known as traffic trunk) from ingress node i to egress node j. Unlike intra-domain TM, inter-domain TM does not specify both ingress and egress points, as traffic travel across domains may enter/leave an AS through multiple border routers, which provides the opportunity for inter-domain TE to select optimised ingress/egress points.

In some scenarios it is possible for an Internet Network Provider (INP) to forecast the traffic matrix before routing optimisation is performed. Currently, there are two principal inputs from which traffic matrix can be forecasted: a Service Level Specification (SLS) and monitoring/measurement (e.g., [28, 29]). An SLS is the detailed information on the agreement negotiated between customers and the INP. By aggregating the traffic predicted in SLSs with individual customers, the INP can estimate the overall bandwidth demand between each pair of ASBRs. In addition, the INP can also apply monitoring/measurement mechanisms at the network boundary for aiding traffic matrix estimation. Having obtained the traffic matrix for the specific network topology, an INP can perform offline TE (i.e., map optimally the whole traffic matrix onto the physical network). Figure 2.2 presents a basic diagram for the offline TE process. One important issue in offline TE is the average duration between two consecutive TE cycles, and this period is known as the Resource Provisioning Cycle (RPC) [30]. In common practice, the RPC for offline TE is weekly or monthly, depending on various factors such as the frequency of establishing, modifying, and terminating SLSs with customers. The major weakness of offline TE is the lack of adaptive traffic manipulation according to traffic and network dynamics , such as traffic burst and network failures. These uncertainties may make offline TE less efficient as the actual traffic pattern might be different from what has been forecasted.

In this thesis, our novel routing strategy for IP-based traffic engineering in access networks will tackle the problem using both an offline and an online approach.

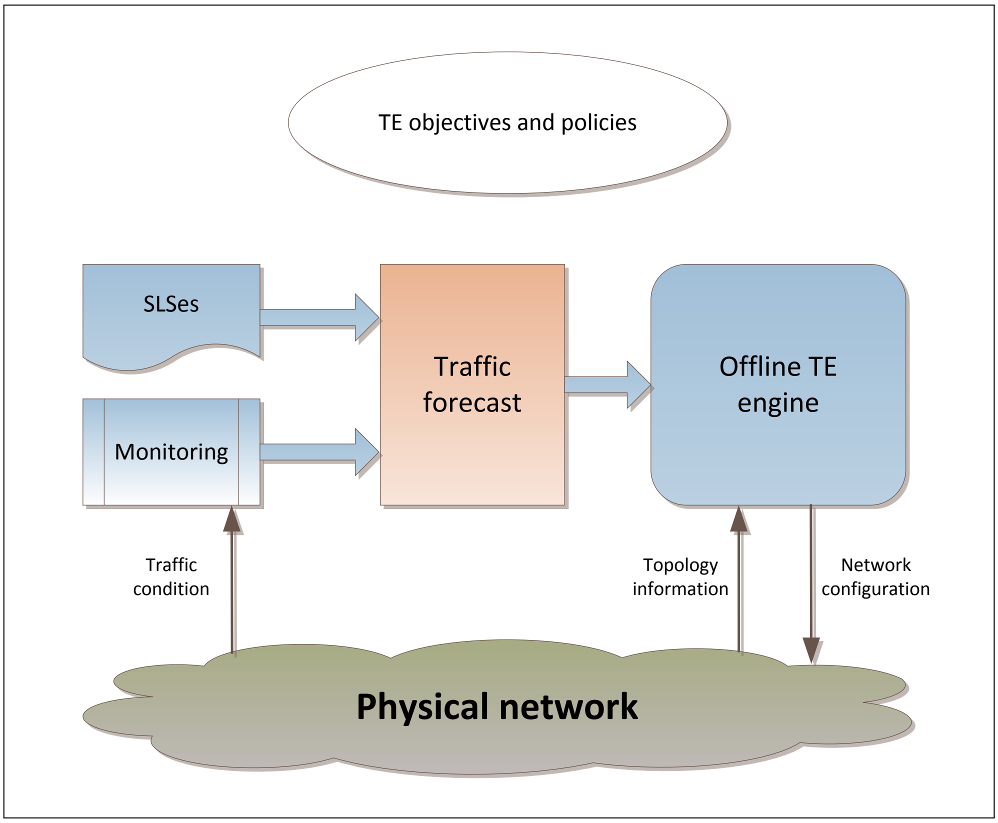


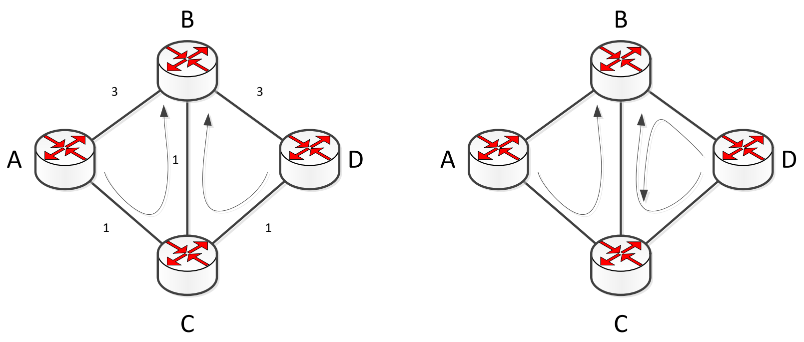
Fig. 2.2 Offline TE mechanism.

2.2.3 Intra-domain IP-based Traffic Engineering

As mentioned above, in our research, we will be focusing exclusively on intra-domain traffic engineering. The advent of plain IP-based traffic engineering solutions has recently challenged MPLS-based approaches in that user traffic can also be effectively tuned through native hop-by-hop-based routing, without the associated complexity and cost of MPLS. In [31] the authors proved that any arbitrary set of loop-free routes can be resolved into shortest paths with respect to a set of positive link weights that can be calculated by solving the dual of a linear programming formulation. This implies theoretically that if a network is optimally engineered through a set of loop-free explicit LSPs, by setting appropriate OSPF/IS-IS link weights, this set of LSPs can be transformed into shortest paths according to this set of link weights.

As a result, plain IP routers can directly compute this set of paths by using Dijkstra's algorithm, and hence the associated LSPs are not required anymore. Let us take an example with a small network as depicted in Figure 2.3a (with symmetric weight setting in both directions of each link): the explicit path set $\{A \to C \to B,\ D \to C \to B\}$ are shortest paths if we assign the weight value of 3 to links (A, B) and (B, D), and set the weight of all the other links to 1. Nevertheless, there are two major issues that restrict the practical deployment of link weight-optimisation-based TE. First, not any arbitrary set of paths can be represented into shortest paths according to a set of link weights. For example, if we add another explicit path $D \to B \to C$ to the aforementioned path set, as shown in Figure 2.3b, these three paths cannot be represented simultaneously as shortest paths with any set of link weights, as the two paths $D \to C \to B$ and $D \to B \to C$ form a path cycle.

As a result, these three paths can be enforced with MPLS explicit routing, but not with IGP link weight setting. Second, the distinct advantage of MPLS-



(a) 2 explicit paths (b) 3 explicit paths

Fig. 2.3 Shortest path representation.

based TE is not only explicit routing, but also arbitrarily unequal splitting of traffic. In this case, even if a set of LSPs can be represented as shortest paths, it is still not possible to unequally split the traffic given the underlying OSPF/IS-IS routers. Evolving from [31], Retravi *et al.* [32] presented further analysis on the relevant issues in shortest path representability. One important contribution from this work is how to prevent unintended paths from becoming shortest paths when setting specific link weights. The authors argue that the network could suffer from traffic suboptimality if some bad paths are included in the shortest path set configured to deliver customers' traffic.

One of the most researched and studied solutions is Equal-Cost Multipath (ECMP) based link weight optimisation. In the ECMP mechanism, if there are multiple shortest paths with equal IGP link weights toward the same destination, traffic is evenly split onto the next hop routers on these paths. Normally, the forwarding behavior in ECMP is on a per flow basis rather than a per packet basis to avoid out-of-order packet arrival. ECMP is a feature of OSPF, which many researchers investigated for path diversity that can achieve load balancing that is comparable to MPLS, by tuning link weights [17]. Fortz and Thorup [17, 26] claimed that by optimising OSPF/IS-IS link weights for the purpose of load balancing, the network service capability can be improved by 50–110% in comparison to the conventional configuration of link weight setting using inverse proportional bandwidth capacity. The key idea of the proposed algorithm is to adjust the weight of a certain number of links that depart from one particular node so new paths with equal cost are created from this node toward the destination. As a result, the traffic originally travelling through one single path can be evenly split into multiple paths with equal OSPF/IS-IS weights based on ECMP. In general, the authors proved that the optimal configuration of such link weights is NP-hard. Figure 2.4 provides a simple illustration of the basic idea of the algorithm. Consider destination node T and assume that part of traffic demand going to T travels through an intermediate node X. Fortz and Thorup's strategy is to split the flow to T going through X evenly along k links (X, X_i), $1 \leq i \leq k$, from X, if these links (X, X_i) belong to the shortest path from X to T. This type of "local adjustment" needs special attention, since shifting traffic might incur additional congestion to other links.

But in reality, ECMP only allows even splitting of traffic, which is not enough to provide an near-optimal and manageable performance comparable to that of MPLS or applicable to IP access networks. In the literature, many have conducted research to avoid problems associated with extra complexity of MPLS, link weight changes that trigger flooding of link-state messages, and even traffic splitting. Authors in [33, 34] proposed a new method based on Multi-Topology OSPF (MT-OSPF) [18]. Also, Wang *et al.* [35] claimed that by partitioning the overall network demand into multiple subsets at the edge of the network so that each of them is delivered through dedicated IP routing topologies, near-optimal performance could be achieved. However, previous conducted research considered multi-topology routing for transit and core networks. Furthermore, research conducted in [36] and [37], among many,

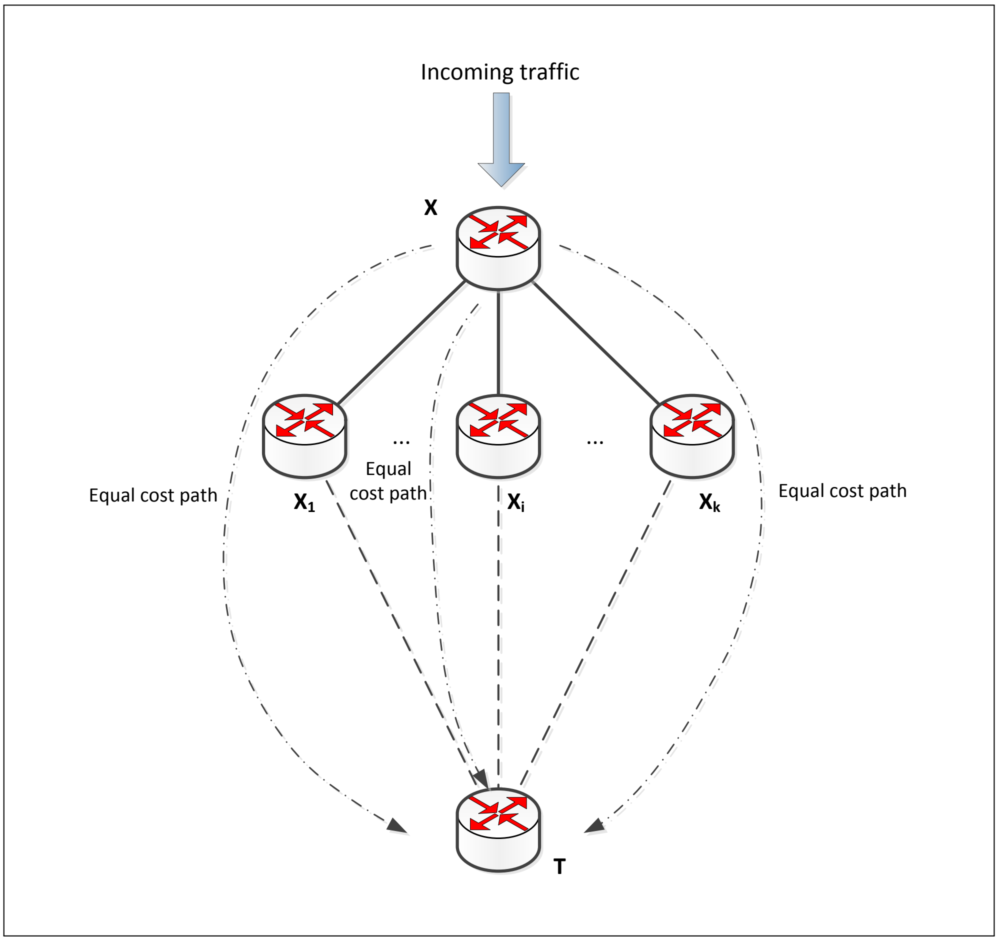


Fig. 2.4 Fortz and Thorup's link weight optimisation solution.

used MT-OSPF for computing back-up routing topologies in case of failures, thus sub-topologies were not used simultaneously for forwarding traffic. The challenges and issues for IP access networks are not alike. Requirement for path diversity and dynamic traffic splitting are exalted due to many routing paths available for unidirectional packet flows between the gateway and the access routers. We consider the transit space to have arbitrary number of meshed routers as forwarding nodes, therefore this strictly follows the rule "smart edge, simple core" rule that was originally designed for the Internet. Secondly, access networks, encounter high traffic variations due to the mobility of users, and variety of applications. Dynamic traffic engineering is hence required that can explore flexibility of path diversity and accommodate maximum levels of QoS for traffic flows.

2.3 Why Do Next Generation Networks Need Path Diversity?

The evolution of network devices, services and applications has reached a phase which imposes to rethink network design, making the case for a clean-slate design of future network paradigms, which are often referred to as "post-IP" solutions. Indeed, network services and Internet applications keep evolving at a very fast pace. Moreover, the explosion of P2P approaches for gaming, telephony and television further blurs the distinction among data, voice and multimedia traffic. Finally, another important piece of the puzzle is constituted by the increase of traffic dynamism, that flash-crowd effects and widespread usage of application-layer overlays undoubtedly contribute to exacerbate.

Due to these new conditions, post-IP network architecture designers are looking, with increased interests towards multi-path routing. Indeed, the situation changed from the early experiences of dynamic routing, whose responsiveness to congestion has refrained its deployment because judged complex and unstable. Nowadays, a number of applications (such as conversational calls and short Web transfers) should still refrain to be split over multiple routes. At the same time, many other applications can tolerate a dynamic environment, which would definitively lead to a more efficient exploitation of the unused network capacity. This is for instance the case of rather bandwidth eager P2P applications, such as file-sharing (e.g. Dropbox or BitTorrent) and live-streaming (e.g. Netflix or Spotify) that together constitute a very significant portion of the aforementioned Internet "data" traffic nowadays.

Our research focuses on the design and evaluation of routing mechanisms in next generation metro access networks. The access network connects a number of equipments aggregating users with various access technologies as WiFi, radio, ADSL, FTTH running different applications. Nowadays ADSL is the main access technology while in the future mobile radio access and FTTH will become more popular enlarging the spectrum of access rates.

Let us focus for instance on the case of a metro-access network with a single gateway towards the big Internet, and define the traffic *local* when it is destined to a host within the access network, or *remote* when it is destined to an Internet host. In the current scenario, traffic is mostly remote (exchanges from *outside* the access network), as most of the services are not provided by the ISP and also a very significant fraction of P2P traffic crosses the gateway to reach faraway Internet hosts.

As traffic and access technologies are changing, the current access ring network is expected to evolve towards more meshed topologies allowing routing to exploit path diversity. In [3], the authors investigated the gains obtained by path diversity within the framework of optimal routing and flow control solved in a number of realistic scenarios. This model takes into account user's access rates, and is thus useful to evaluate the performance of networks whose users have heterogeneous *access technologies*. Muscariello *et al.* evaluated the benefits of path diversity for a wide range of scenarios – i.e. for various network topologies, individual link capacities, access technology popularity and traffic locality. They set up a multi-path routing framework in which the objective is to maximise the user utility $U(\cdot)$ and introduce a network cost $C(\cdot)$ that can be thought as modelling the link delay (mean delay in an $M/M/1$ queue), expressed as follows:

$$C(x_{ij}) = \frac{x_{ij}}{c_{ij} - x_{ij}} \tag{2.1}$$

$$U_d(x) = w_d(1-\alpha)^{-1}x^{1-\alpha} \tag{2.2}$$

Where x_{ij} represents a share of the capacity c_{ij} of link (i, j), d a network flow and α a fairness criterion that tends to $+\infty$.

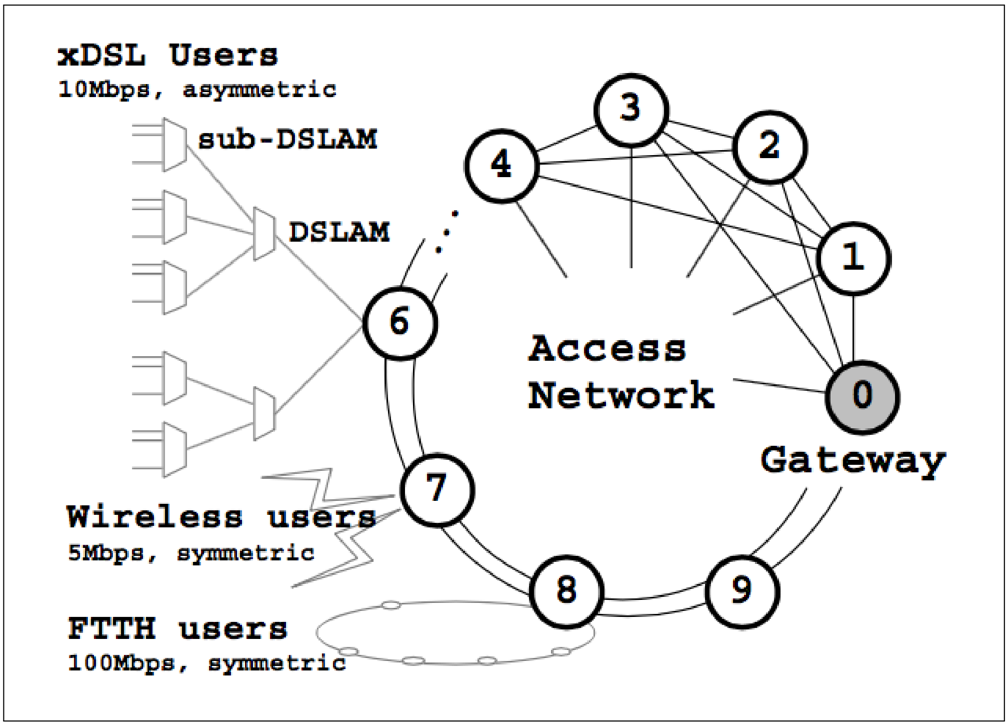


Fig. 2.5 Future access network reference scenario.

By modelling a heterogeneous population of users that access the network via different technologies the authors in [3] explored a wide range of scenarios. The reference network and traffic scenarios used are illustrated with the help of Figure 2.5 and Table 2.2.

Nowadays, most users have xDSL access technologies while FTTH and Wireless are exploited by a smaller number of people: however, FTTH subscribers are growing extremely fast. At the same time, in the future we will likely assist

Table 2.2 Muscariello's current and future reference scenarios.

		Current	**Future**
Access Type	Internet gateway	0	0
	ADSL	1-6	1-3
	WiFi	7,8	4-6
	FTTH	9,10	7-10
Traffic Type	local (1-10)	25%	25%
	hot-spot (0)	75%	75%

to an increased heterogeneity of access types, e.g., due to the deployment of new technologies, such as WiMAX/LTE. However, it is unlike that a single technology will entirely take over the others; instead, it is more reasonable to envision that users will likely use different technologies depending on their location, and even use several technologies at the same time.

In the end, it is observed that multi-path, thanks to path diversity, is able to more efficiently exploit additional available capacity to fulfil additional demands, and better use existing resources, potentially avoiding the need for costly links capacity upgrades. Multi-path routing reduces the extent of the link capacity upgrade by almost a factor of two which confirms it to be an appealing strategy for both current and future network architectures.

In our research, not only will we support and confirm this statement, but also use it as a foundation for our proposal to enhance routing for traffic engineering in future access networks.

2.4 Quality of Service Protocols

In recent years, the multimedia services have become the most significant applications among users in the Internet. A new generation of multimedia services is considered as a solution to create new revenue streams for the subscriber-saturated networks. What is certain is that the success cannot be achieved unless the quality of service meets the users' expectation. This section describes the most important QoS mechanisms used in IP-based networks.

2.4.1 Integrated Services

The development of the Integrated Services (IntServ) architecture model [38] was motivated by the poor performance of real-time applications across the Internet, mainly caused by the variable queueing delays and congestion losses. The Internet, as originally conceived, offers only a best-effort data delivery. Therefore, a new service model of the Internet, capable of providing some control over end-to-end packet delays, was a prerequisite for new generations of Internet applications. Another motivation for developing IntServ model, apart from guaranteeing real-time QoS, was a rising demand for controlling the allocation of bandwidth among different classes of traffic. Network operators were requesting a system model capable of dividing traffic into a few administrative classes and assigning to each a minimum percentage of the available bandwidth under overload conditions. To this end, IntServ was introduced by the IETF as a new Internet service model. Being capable of explicitly managing network resources, IntServ can provide an end-to-end QoS to certain flows. In addition to the best-effort, IntServ supports two types of services: controlled-load service and guaranteed service.

The controlled-load service [39] is closely equivalent to the best-effort delivery in a lightly loaded network. Applications using this model can assume that the packet loss rate is almost equal to the basic packet error rate of the transmission medium, meaning that a very high percentage of transmitted packets will be delivered successfully. The service also guarantees that a very high percentage of the delivered packets will experience a delay which does not exceed by a great extent the minimum delay experienced by any successfully delivered packet.

However, the specific target value cannot be requested for delay, and neither for the loss rate in the controlled-load service. To ensure that these conditions are met, users provide the en-route network elements with an estimation of the data traffic they will generate, indicated in the flow's Traffic Specification (TSpec), asking adequate bandwidth and packet processing resources for the lifetime of the flow. The controlled-load service is intended to support a broad class of applications which have been developed for use in today's Internet, but are highly sensitive to overloaded conditions.

The guaranteed service [40], on the other hand, is intended to emulate, over a packet-switch network, a dedicated rate circuit. Not only does this service provide applications with a bandwidth guarantee, it can control the maximum end-to-end queuing delay. It also guarantees that packets will not be deleted due to the buffer overload, provided the flow's traffic stays within its specified traffic parameters. The guaranteed service, however, does not control the minimal or average delay. Not being justified for all applications due to the cost aspect, such guarantees are required for applications with hard real-time requirements such as remote process control, tele-medicine, etc [41].

The IntServ provides different controlled levels of packet delivery services for applications. However, supporting this capability requires two conditions. First, both applications and all individual network elements along the path must support mechanisms to control the QoS delivered to those packets. Second, there should be a mechanism to convey QoS management information between the application and en-route network elements [42]. While the former is provided by QoS control services such as controlled-load and guaranteed services, the latter is frequently implemented by a resource reservation set-up protocol such as RSVP.

2.4.2 Resource ReSerVation Protocol

RSVP is a reservation set-up protocol for IntServ-based IP networks. It is a soft state, receiver-oriented signalling protocol, that can reserve resources for unicast and multicast applications. RSVP is used by both endpoints and routers. End-points utilise RSVP to request a specific QoS level for their flows. Subsequently, routers use RSVP to inform all network elements along a flow's path(s) to deliver and maintain the required QoS throughout the transmission. RSVP is not a routing protocol, however, it strongly depends on present and future routing protocols to determine where it should carry the reservation request. RSVP conveys three different types of information:

- **Sender-generated information:** this information describes the characteristics of the data traffic the application expects to generate (the Sender TSpec), and the format of data packets the sender originates i.e., the sender IP address and optionally the UDP/TCP sender port (the Sender Template). These parameters flow downstream towards the receiver without being modified by the intermediate nodes.

- **Intermediate-node-generated information:** this information is generated or modified by the intermediate nodes along the path between the sender and receiver. It describes the properties of data path, including the availability of specific QoS control services and parameters required by them to operate correctly.

- **Receiver-generated information:** this information specifies the receiver's desired QoS (the FlowSpec) and a set of data packets to receive the requested QoS (the FilterSpec). The former, the FlowSpec, includes the receiver's desired integrated service type (guaranteed or controlled-load), the traffic characteristics of the data flow for which the resources should be reserved (the Receiver TSpec), and if the guaranteed service was selected, other information required to invoke this service (the RSpec). The latter, the FilterSpec, together with a session specification, defines a set of data packets to receive the requested QoS. The receiver generated information follows exactly the reverse path the data packets will use, upstream to the sender.

During its life-time, RSVP has received substantial research community attention being one of the most persistent and altered protocols. In turn it has not escaped criticisms for its complexity, and potentially bad scalability, especially in the Internet core. In RSVP, the amount of state information is directly proportional to the number of flows, implying a massive processing and storage overhead on the core routers. Nevertheless, instead of being abandoned, over the years several extensions to alleviate the crises have been proposed. The most recent up-to-date survey of the RSVP extensions can be found in [43].

2.4.3 Differentiated Services

The Differentiated Services (DiffServ) [44] effort in IETF has developed a simple model to differentiate the qualities of packet delivery. The intent of the DiffServ model is the provision of scalable service discrimination in the Internet with no need to have per-flow state and signalling in every router. The model achieves scalability and flexibility by separating the architecture into two major components: forwarding path and management plane [45].

The forwarding path behaviours, also called Per-Hop Behaviours (PHB), include the differential treatment an individual packet receives at each router's output interface queue along its path, implemented by queue management disciplines, e.g., Weighted Round-Robin (WRR). Within the backbone of the network, each router selects a particular forwarding behaviour for packets based on the value of the DiffServ Code Point (DSCP) set in the IP packet header, without having to know which flows or what types of applications the packets belong to. The process of setting the DSCP in a packet based on defined rules, or marking, is performed at network edges, the sender or first-hop router, and administrative boundaries.

The management plane, on the other hand, involves the configuration of network elements with respect to which packets get special treatment and what kinds of rules are to be applied for allocating adequate resource to each treatment in each router. A logical entity such as bandwidth brokers is in charge of resource management in an administrative domain. In the DiffServ model, packets can behave as follows:

- **Default PHB:** The default PHB [45] provides the common, best-effort forwarding behaviour available in existing networks. Packets belong to this aggregate when either no other agreements are in place, or when the DSCP value is not mapped to any of the available PHBs.

- **Assured Forwarding PHB:** the Assured Forwarding (AF) PHB [46, 47] provides four different forwarding assurances/classes in ascending order of priority where each one is allocated a certain amount of buffer space and interface bandwidth. Within each AF class the IP packets are marked with one of three levels of drop precedence. The assigned drop precedence reflects the relative importance of the packet within its class in case of congestion, wherein packets with a higher drop precedence will be discarded in favour of ones with a lower value. AF is a rough equivalent of the controlled-Load services defined in the IntServ architecture.

- **Expedited Forwarding PHB:** almost similar to the guaranteed service in the IntServ, the Expedited Forwarding (EF) PHB [48] intends to provide a low loss, low delay, and low jitter service in DiffServ domains. Such a service, when implemented, provides a premium service such as a point-to-point connection or virtual leased line. However, for optimal efficency it should be reserved for only the most critical applications, clearly because in case of congestion it is impossible to treat all or most traffic as high priority.

The Internet is composed of several domains managed by administrative authorities based on different policies. That means the forwarding services provided by a sender domain based on the contracted SLA may not be compatible with the ones provided by other domains. This is due to the fact that the packet handling in DiffServ architecture is left to each administrative domain. Consequently, the DSCP chosen for packets by the sender may change on their way towards the receiver. Therefore, a packet marked with a high priority may be regarded as a low priority or even best-effort, resulting in a violation of service quality. Although it is strong on simplicity, DiffServ is weak on guarantees. And finally, it does not offer any receiver control.

2.5 Mobility Management

Internet Protocol assumes that a node's IP address uniquely identifies its physical attachment to the Internet; hence, in order to receive packets destined to the node, it should be attached to the network indicated by its IP address. Although working well under such assumption, IP cannot meet the needs of the burgeoning population of mobile users who wish to change their point of attachment from one network to another without losing their ability to communicate. To that end, Mobile IP protocol was developed as a scalable mechanism for accommodating node mobility within the Internet. While being the standard network-layer solution, Mobile IP is not the only proposed mechanism. An overview of existing protocols for mobility management in IP networks is given in [49, 50].

This subsection introduces the main concept of Mobile IP, and different mobility management approaches used to design local mobility management for Mobile IP (basis for Chapter 5).

2.5.1 Mobile IP

Mobile IP protocol [51], introduced by IETF, is the standard network-layer, mobility-enabling protocol for the Internet. It enables a Mobile Node (MN) to change its serving network without need of changing its permanent IP address. This is accomplished by providing an MN with two IP addresses: Home Address (HoA) and Care of Address (CoA). The former is a long-term IP address obtained by an MN on its home network, administrated in the same way as a permanent IP address is provided to a stationary node. The MN is always identified by its HoA, regardless of its current point of attachment to the Internet. The latter, the CoA, is a temporary IP address obtained by the MN whenever it moves to a foreign network. The CoA reflects the MN's current location in the Internet. The MN operating away from home needs to register its new CoA with its home agent, informing it about its current location. All the packets destined to the MN are then intercepted and tunnelled by the HA to the MN's new CoA. By using this mechanism, the MN can continue its ongoing communication with Correspondent Nodes (CN) after moving to a new IP subnet, while keeping its movement transparent to the higher-layer protocols and CNs.

2.5.2 Localised IP Mobility Management

Mobile IPv6 empowers users to move freely within the Internet while still keeping their on-going connection(s), however, this comes at the cost of transferring signalling messages to the Home Agent (HA)/CN after each layer-3 handover (henceforth referred to as handover in this document). The process of exchanging the Binding Update (BU) and the Binding Acknowledgement (BA) can cause significant delays or disruptions on active connections if the HA/CN is far away. Some packets will be lost. Together with link layer and IP layer connection set-up delays, there may be effects to upper-layer protocols. Moreover, the signalling exchanges can increase the signalling overhead on the network especially on a wireless link, and finally it can jeopardise the location privacy of the MN.

To alleviate such performance problems, a number of Localised Mobility Management protocols have been proposed, intending to maintain the IP connectivity and reachability of an MN when it moves, while confining the mobility management signalling to an access/local domain. Although using different approaches, i.e., host-based or network-based to be described later in this section, all the proposed solutions utilise a new entity defined as a local home agent, a home agent closer to the MN. The MN's movement over the local domain, local mobility, requires only signalling exchanges with the MN's local home agent. This is in contrast with the Global Mobility Management protocols such as Mobile IP which invalidates an MN's global unicast IP address after each handover, causing a global, end-to-end routing of signalling messages between the MN and CN/HA. Note that local domain is a generic term for a collection of fixed and mobile network components allowing access to the Internet all belonging to a single operational domain. Depending on the access technology, geographically the area can be large.

Host-based Mobility

The host-based mobility management protocols require a mobile user involvement at the IP layer. The user needs to take care of the signalling required to manage its mobility, and be aware of the local/micro and global/macro mobility management solutions, thus acting accordingly. One of the most successful solutions for the host-based mobility management is HMIPv6 protocol [52]. As a simple extension to Mobile IP, its intent is to improve the performance by handling MNs' mobility within a local region locally. The protocol utilises a new entity called the Mobility Anchor Point (MAP). The MAP is a router located in a visiting domain, usually at the gateway, acting as a local home agent. Its domain's boundaries are defined by the means of router advertisement messages advertising the MAP information to MNs.

Upon entering a new MAP domain, the MN configures two addresses: Local Care of Address (LCoA) and Regional Care of Address (RCoA). The former is the on-link CoA configured on an MN's interface, based on the prefix advertised by its default router. This address defines the current location of the MN within the MAP domain. It changes when the MN moves from one subnet to another both belonging to the same MAP domain (local/micro mobility). The latter, the RCoA, is formed in a stateless manner by combining the MN's interface identifier with the MAP's subnet prefix obtained from the MAP option in router advertisement messages. The RCoA changes when the MN moves from one subnet to another each belonging to a different MAP domain (global/macro mobility). After IP-layer configuration, the MN needs to register with its local home agent, the serving MAP, by sending it a local BU. The message contains the MN's RCoA (similar to a home address) and LCoA. The MAP will then return a BA to the MN. If the registration is successful, the bi-directional tunnel is established between the MAP and MN. After receiving the BA from the MAP, the MN should register its new RCoA with its HA/CN by sending a BU to each, as in Mobile IPv6. The message will bind the MN's original home address to the newly- configured RCoA. The confirmation of registration, the BA, will be sent to the MN. Following the successful registration, packets sent by the HA or CN to the MN will have the MN's RCoA in their destination address. The MAP, as a local HA, intercepts the packets and tunnels them to the MN's LCoA. Similarly, all packets sent by the MN are tunnelled to the MAP, having the MN's LCoA and MAP's IP address as a source and destination address in their outer header. The inner header contains the MN's RCoA as a source address and the HA/CN IP address as the destination address.

Based on this architecture, the MN's location inside the MAP domain remains transparent to all the nodes it communicates with but the MAP. Moreover, instead of exchanging a pair of BU/BA with the HA and CNs after each handover, the MN just needs to register with the MAP, as long as its movement is confined to within the MAP domain (intra-domain handover). This results in a smaller signalling overhead in comparison with Mobile IP.

Network-based Mobility

Host-based mobility protocols require changes in MNs' software stack that may not be compatible with all global mobility protocols. Although the existing localised mobility management solutions all depend on Mobile IP or derivatives, future MNs may select other global mobility management protocols, such as Host Identity Protocol (HIP) [53]. Moreover, considering the resource constraint characteristic of mobile devices and users reluctance to host stack software modification [54], having a mechanism that relocates mobility procedures from MNs to network components has become an issue of great interest in recent years.

To that end, Network-based Localised Mobility Management (NETLMM)

approach [54] was introduced to enable IP mobility for an MN without its participation, and therefore, it requires no software changes on the host. PMIPv6 [5] is the protocol standardised by IETF to provide this approach.
The core functional entities in PMIP are: the Local Mobility Anchor (LMA) and Mobile Access Gateway (MAG). Acting as a local home agent in the PMIP domain, the LMA (usually located near the gateway) manages the MN's mobility inside domain under its control. It maintains a collection of routes for individual MNs and manages their binding states. The latter is the PMIP-enabled access router responsible for tracking the movements of the MN and initiating the required IP-layer mobility signalling on its behalf. A high-level representation of a PMIPv6 network is depicted in Figure 2.6.

An MN entering a PMIP domain will be first identified by a serving MAG which the MN attached to its access link. The identification is performed by means of an MN identifier. Every MN roaming within the PMIP domain should have a unique identifier, such as a Media Access Control (MAC) address. The MN identifier has an associated policy profile, accessible by network entities i.e., MAG and LMA, that identifies the MN's serving LMA IP address (mandatory field), permitted address configuration modes, roaming policy, and MN's home network prefix. After a successful authorisation, the MAG sends a Proxy Binding Update (PBU) message to the LMA, informing it of the current location of the MN. The message contains the MN identifier for identifying the MN. On receiving the message, the LMA sets up its endpoint of bi-directional tunnel to the MAG, binds the MN's home address prefix to the MAG's address, and replies back by sending a Proxy Binding Acknowledgement (PBA) message including the MN's home network prefix. On receiving the acknowledgement, the MAG configures its endpoint of the bi-directional tunnel to the LMA. Having the knowledge of the MN's home network prefix allows the MAG to emulate the MN's home link. It puts this prefix in the router

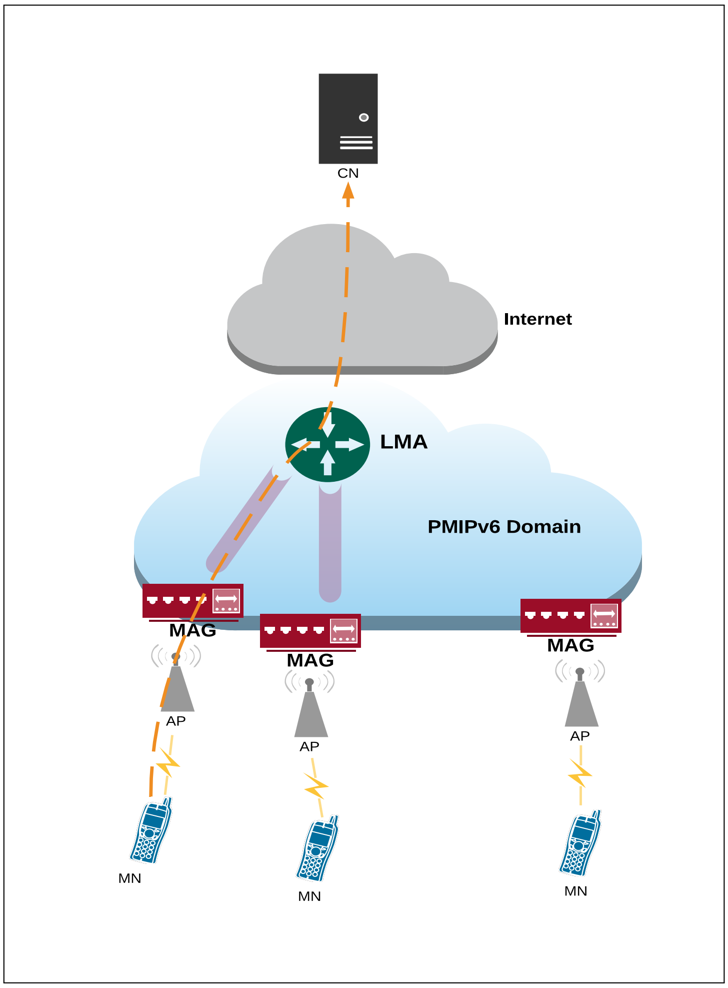


Fig. 2.6 PMIPv6 high-level network architecture.

advertisement message and sends it to the MN. The MN, on receiving the same home network prefix, starts to configure its IP address without detecting any change with respect to the Layer-3 attachment of its interface. As far as the MN is concerned, it is still in its home network. The LMA as a topological anchor point for the MN's home network prefix, intercepts all the packets destined to the MN's home address and sends them to its serving MAG through the pre-defined bi-directional tunnel. Packets sent by the MN will be received by the serving MAG and tunnelled to the LMA. The LMA, on receiving the packets, removes the outer header and routes them to the destination, the CN.

2.6 Towards 2020

The use of mobile communication networks has increased significantly in the past decades, in terms of complexity of applications, their required capacities, and heterogeneity of device types. So far, this trend has always been met by significant technological advancements and will continue to increase. By 2020, Europe has to pave the way for a new generation of converged wired and wireless communication networks, which has to be developed and deployed to move forward to a future networked society.

Networks close to the customers, namely access/backhaul networks, have received little attention in the literature compared with core and transit networks when it came to routing optimisation and traffic engineering. In this thesis, we present our perspective on a 5G access network and focus especially on the arising challenges associated with traffic engineering. Looking back at the development of 3G (UMTS, HSPA) and 4G (LTE, LTE-Advanced) it is clear that these generations of mobile networks focused on creating new physical radio transmission schemes in order to meet new capacity requirements.

Furthermore, in order to address the user-oriented challenges, we foresee a continued evolution of existing functions, e.g., network densification into Ultra-Dense Networks (UDNs) and device-to-device communications. Indeed, small access nodes, with low transmit power and no precise planning requirements, are conceived to be densely deployed, resulting in a UDN. This approach will improve spectral efficiency by reducing the distance between transmitters and receivers, and to improve macrocell service by offloading wireless traffic, thus freeing radio resources in the access. Network densification is a way to increase the capacity and datarate towards 2020. In this light, throughout this thesis, we have imagined and used a full IP-based non-standard access network architecture, in line with that of the IST BRAIN Project for systems beyond 3/4G

[4].

Finally, an extensive deployment of small access nodes induces several challenges such as an adverse interference scenario (outside the scope of this work) or additional mobility management requirements. However, traffic engineering with mobility support in PMIP-enabled networks have, to our knowledge, not been studied. This research thus proposes a traffic engineering solution with mobility management for access networks with the presence of mobility agents.

Chapter 3

Multi-Plane Routing in IP Access Networks

The main motivations for the investigation of a next generation access network based on IP technology fall into three categories: those of interest to accountants, those of interest to engineers, and those of interest to end users.

For reasons of economy, interest to accountants, mobile network infrastructure should be based on the prevalent fixed networking standard. Considering that even video entertainment is delivered over IP, there is no doubt that IP is the correct future proof choice. There are two major aspects to this. First, IP is becoming ubiquitous. Second, there are economies of scale, both in capital and operational expenditures.

The second motivation relates to advantages that are visible directly to engineers. There is a growing consensus in the networking community that the philosophy embodied in the IP protocol suite has benefits over more traditional (connection oriented, cell or frame switching) networks. These benefits include keeping the network simple and pushing complexity to the edge of the network which makes the network cheap to install and administer. Making the network flexible and scalable in turn makes the network functionality simple to evolve and adaptable as well as making the network homogeneous. By homogeneous we mean a common access network consisting of different wireless technologies [2, 55]. Finally, the last motivation concerns the benefits seen from end users (or at least, the devices they own). We assume that in the near future, all end user applications will be natively IP-based. This can already be observed for example with voice traffic, VoIP.

The rest of this chapter is organised as follows: we will present the motivations and related work for our novel Multi-Plane Routing (MPR) mechanism in Section 3.1. We will then describe the theoretical foundation of MPR in Section 3.2. Furthermore, Section 3.3 will elaborate on the network model and the core-functioning of MPR. The simulation setup and scenario will be described in Section 3.4 followed by the performance evaluation in Section 3.5. Section 3.6 will finally conclude the chapter.

3.1 Motivation and Related Work

3.1.1 Motivation

Today, most access networks use Cisco MPLS which enables Entreprises and Service Providers to build intelligent networks that deliver services over a single infrastructure. MPLS [56] is a flow-based packet forwarding technology, built on ATM, that assigns packet flows to Label Switched Paths (LSPs). The most distinct advantage of MPLS is its capability of explicit routing and arbitrary splitting of traffic. However, since traffic trunks are delivered through dedicated LSPs, scalability and robustness becomes an issue. First, MPLS has been only deployed in core networks. Second, the overhead of setting up LSPs can be very high in large-size access networks, making it less scalable due to the number of dedicated LSPs to set up. Third, MPLS is more complex and less robust than its counterparts IP routing protocols, e.g., OSPF.

The latter is the most widely used intra-domain routing protocol in today's Internet. OSPF is an *adaptive* link-state routing protocol that operates directly over IP. Forwarding decisions are exclusively based on the destination address in packets' IP headers. Each router within an OSPF area possesses information about the complete network topology detecting changes in the topology such as link or node failures. When a link breaks, its end nodes flood the network with the new state information and very quickly converge on a new loop-free routing structure. Therefore, the flooding process is only triggered upon detection of a link-state change. A more comprehensive comparison between MPLS and OSPF for Traffic Engineering (TE) is available in [57]. On one hand, OSPF is simple, robust, and highly scalable. On the other hand, OSPF only supports "best effort" traffic, hence suffering from bad performance if TE is not correctly implemented. A question arises as to how OSPF can approach the MPLS performance while keeping its advantages.

In this thesis, we focus on the next generation all-IP metro access network architectures. The chosen reference scenario topology represents an Internet domain organised according to cellular principles [55, 58].

3.1.2 Related Work

To answer the question posed in the latter section, some of the research results proposed to use the Equal Cost Multi-Path (ECMP) feature present in OSPF and to tune the link weights in order to achieve load balancing in OSPF that is comparable to MPLS networks [17]. However, practically, ECMP solely supports even traffic splitting, which is not enough to approximate the optimal result as in MPLS. Wang *et al.* [36] claimed that by partitioning the overall network demand into multiple subsets at the edge of network so that each of them is delivered through dedicated IP routing topologies, near-optimal TE performance could be achieved. Also, authors in [33, 34] proposed a new method based on related multi-topology routing techniques, such as Multi-Topology OSPF/IS-IS [18, 59]. Note that our strategy is different from that of multiple overlay networks which have a number of scaling issues [31]. Overlay routing does not split the flow among all available paths but selects the best path. With the MPR approach, IP routing runs natively over the physical topology rather than over the virtual network. In [33, 34], when the changes of network state are detected, the flows are re-mapped to the logical topologies. However, dynamic mapping from flows to logical topologies may cause traffic instability.

The main contributions of this chapter are threefold. Firstly, we developed an algorithm for building a set of logical planes in an offline fashion under the future all-IP access network topology. Secondly, our approach does not require frequent and on-demand re-assignment of OSPF link weights, hence reducing the re-convergence time and traffic instability. Thirdly, our simulations based on realistic applications models have shown that our approach can lessen the maximum link utilisation (MLU) and the maximum link delay (MLD) by 40% and over 90% respectively if 5 RPs were used.

3.2 Theoretical Foundation: Multi-Plane Routing

In this section, we introduce the multi-plane routing strategy. We start by describing its principle and secondly, we present the algorithm for building the routing planes with the objective of maximising path diversity.

3.2.1 MPR Method Overview

MPR allows the routers within an area to maintain several *independent* logical planes, with independent set of link weights, and hence independent routing tables for each routing plane (RP). Each RP is an instance of OSPF from which a subset of the physical links have been removed for carrying traffic. Therefore, an RP is a subset of the underlying network (or physical topology). It can overlap with another or share any subset of the underlying network. In standard OSPF, as shown on the left-hand side of Figure 3.1, one routing information base (RIB, or routing table) is extracted from the topology database, and subsequently, one forwarding information base (FIB, or forwarding table) is used. With MPR, bold lines in Figure 3.1, it is not one RIB and one FIB

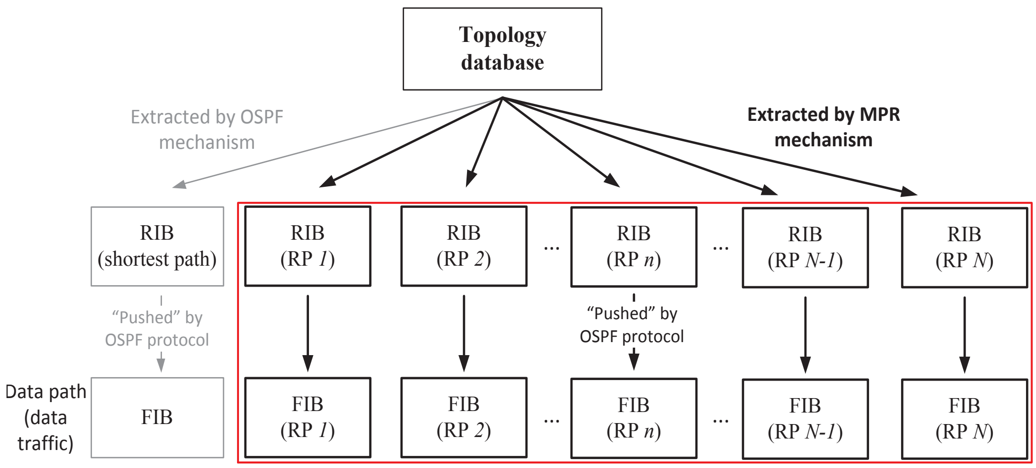


Fig. 3.1 Data flow under conventional routing (left, thin grey lines) and under MP routing (right, thick black lines).

that are used but instead, one RIB/FIB per plane. Data traffic is mapped to a specific routing plane that a router selects, and is routed according to the corresponding RIB. MPR can be used, for example, to define separate planes for different class of traffic. It is outside the scope of this thesis to specify how the information in various plane specific forwarding structures is used during packet forwarding or how incoming packets are associated with the corresponding routing plane, however some proposed possible ways for mapping traffic to Routing Planes (RPs) [33, 36].

Our approach comprises one main task, namely offline network dimensioning through link weight optimisation for achieving maximum path diversity across multiple routing planes. This task is agnostic to traffic matrices, signifying that the input to the MP link optimisation algorithm only encompasses the physical network topology. Earlier studies [36, 60, 61] of practical algorithms for creating routing planes showed that $3-5$ planes were sufficient to achieve near-optimal TE performance.

Figure 3.2 depicts a simple example of how four routing planes can be set up in a simplistic topology. The left subfigure shows the path between source S and destination T in all four routing planes whereas the right subfigure indicates a possible link weight configuration for one of the routing plane. The cost of a path, which is the sum of the link weights along the path, has to be the lowest for this path in order to be considered a shortest path (OSPF).

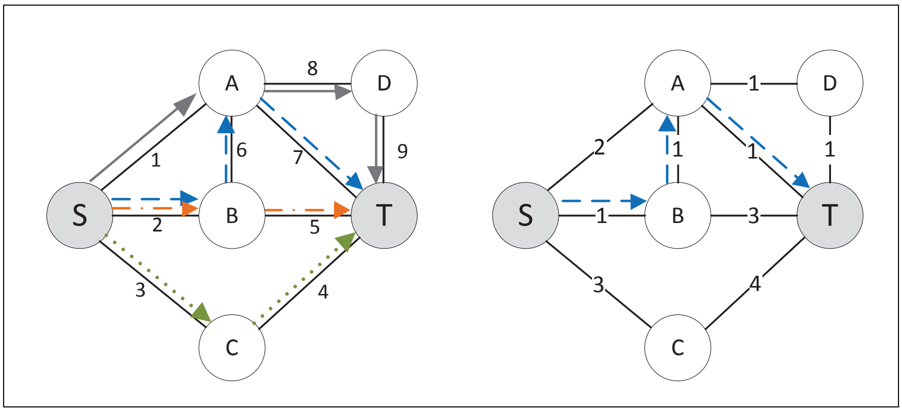


Fig. 3.2 A simple example of 4 RPs. Numbers indicate link IDs (left) and link weights for one RP (right).

3.2.2 Constructing the Routing Planes

This subsection addresses how the planes should be created to efficiently facilitate load balancing and path diversity in the network. In our approach, we distinguish between the default plane which is the standard flat OSPF network topology where all the links can be used for carrying traffic and the routing planes where a set of links are excluded from the routing process. We propose building a set of routing planes with three important properties:

1. Each link must not be used for routing in at least one routing plane.

2. All planes are connected which means, in each plane, there is a valid route between each gateway (GW)-Access Router (AR) pair. All nodes in between are considered transit routers, they are not traffic sources or sinks.

3. Each link is used in at least one plane. This property ensures maximum path diversity and justifies the use of the chosen network topology (relaxed-tree), refer to Section 3.3.

3.3 MPR Solution: Network Model and Fundamentals

We describe the problem of creating routing planes for multi-plane routing in graph-theoretical terms as follows. For a given communication access network, its topology is mapped to the corresponding undirected graph $G = (\mathscr{V}, \mathscr{E})$. The network consists of a set $\mathscr{E}$ of E ($\mathscr{E} : e = 1, ..., E$) unidirectional edges with finite capacities $C = \ (C_e,\ e = 1, ..., E)$ and a set $\mathscr{V}$ of V ($\mathscr{V} : v = 1, ..., V$) vertices. Let $\mathscr{N} : n = 1, ..., N$ be the set of routing planes and each edge $e \in \mathscr{E}$ be assigned with $|N|$ distinct link weights (denoted by $w_n(e),\ n \in \mathscr{N}$). The network also supports a set $\mathscr{D}$ of D ($\mathscr{D} : d = 1, ..., D$) aggregate traffic demands between the gateway and each access router. For example, $d = 1$ represents the total traffic demand between the *GW* and *AR1*. Let also $\mathscr{P}$ be the total set of available paths for each demand d in all RPs in $\mathscr{N}$ (we consider only symmetric routing). Therefore there are $P_n^d \in \mathscr{P}$ acyclic shortest paths for demand d and routing plane n according to the link weight configuration W_n for that routing plane. They are represented by an $N \times E$ matrix R^d , where $R_{en}^d = 1$ if path of pair d uses link e in routing plane n, and $R_{en}^d = 0$ otherwise. The overall routing matrix, whose dimension is $E \times (N \times D)$, is given by:

$$R = \begin{bmatrix} R^1 & R^2 & \cdots & R^D \end{bmatrix} \tag{3.1}$$

For example, as shown in Figure 3.2, an eight-link network supports one demand (between S and T), and the corresponding routing matrix is:

$$R^1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \tag{3.2}$$

The general routing matrix for demand d can now be formerly rewritten as follows:

$$R^d = \begin{bmatrix} R_{11}^d & R_{21}^d & \cdots & R_{E1}^d \\ R_{12}^d & R_{22}^d & \cdots & R_{E2}^d \\ \vdots & \vdots & \ddots & \vdots \\ R_{1N}^d & R_{2N}^d & \cdots & R_{EN}^d \end{bmatrix}^T \tag{3.3}$$

With $\forall d \in \mathscr{D},\ \forall n \in \mathscr{N},\ and \forall e \in \mathscr{E}$. The link weight assignment mechanism [62] aims at maximising path diversity in network and uses the following steps. definition

Step 1 *Link weight assignment with path diversity maximisation.*

The algorithm starts by generating a random set of R^d_{en} for all demands $d \in \mathscr{D}$ and routing plane $n = 1$ (recall that RP 0 is the physical topology). Then, we introduce the *path diversity index* for building planes $n > 1$, $n \in \mathscr{N}$. plain

Definition 1 *Our definition of path diversity across multiple routing planes is as follows. We introduce the Path Diversity Index (PDI) for each demand $d \in \mathscr{D}$ and for each link $e \in \mathscr{E}$ as the number of planes that include e in their shortest paths for demand d (between each GW-AR pair), formally*

$$PDI^d_e = \sum_{n \in \mathscr{N}} R^d_{en}, \; \forall e \in \mathscr{E} \tag{3.4}$$

Our first objective is to minimise the chance that for a given demand all routing planes share a single link; secondly, to maximise the chance that any single link is used in at least one plane. The reason for this is if congestion or failure occurs the associated demand can avoid this particular link and secondly, to ensure the link will not be left unused for carrying traffic.

Definition 2 *Towards this end, we specify Full Path Diversity Index (FPDI), which designates whether a critical link e is included in the shortest paths for demand d in all routing planes*

$$FPDI^d_e = \begin{cases} 1, & \text{if } PDI^d_e = |N-1|; \\ 0, & \text{otherwise.} \end{cases} \tag{3.5}$$

In summary, the link weight assignment problem is formally described as follows: to calculate $|N|$ sets of positive link weights $W_n = \{w_n(e)\} : \; 1 \leq w_n(e) \leq K$, with $\forall n \in \mathscr{N}$, $\forall e \in \mathscr{E}$ and K $(= 2^{16} - 1)$ the highest weight value that OSPF can handle, in order to maximise

$$\sum_{d \in \mathscr{D}} \sum_{e \in \mathscr{E}} FPDI_e^d \tag{3.6}$$

In order to perform the link weight assignment, we introduce a function f such that

$$\begin{aligned} f : \mathbb{N} &\longmapsto \mathbb{Z} \\ m &\longmapsto 2^m + m \times (K - 2^m) \end{aligned} \tag{3.7}$$

This function has the following purpose: it converts 0 to 1 and 1 to K and will be used for the link weight assignment. Recall that a shortest path routing protocol such as OSPF computes the paths based on the sum of the weights associated with the links along the paths. This means that a router will select the path with the least cost (sum of the weights). By setting a link weight to K, we ensure the link will not be selected, thus not being included in the shortest path for demand d. Function (3.7) performs the following task

$$\begin{aligned} & \quad\; f \\ R^d_{ep^d_n} = 0 &\longrightarrow w_n(e) = f(R^d_{ep^d_n}) = 1 \\ R^d_{ep^d_n} = 1 &\longrightarrow w_n(e) = f(R^d_{ep^d_n}) = K \end{aligned} \tag{3.8}$$

Finally, we can express W_n, the link weight configuration for routing plane n, as:

$$W_n = \begin{bmatrix} f(R^1(n,1)) & f(R^1(n,2)) & \cdots & f(R^1(n,E)) \\ f(R^2(n,1)) & f(R^2(n,2)) & \cdots & f(R^2(n,E)) \\ \vdots & \vdots & \ddots & \vdots \\ f(R^D(n,1)) & f(R^D(n,2)) & \cdots & f(R^D(n,E)) \end{bmatrix} \tag{3.9}$$

Step 2 *Traffic splitting ratio assignment.*

In the simulated scenario, traffic splitting ratios are fixed and pre-computed as follows. We introduce ψ_n^d as the traffic splitting ratio of demand d at GW on routing plane n and θ_n as the *branching factor*.

$$\psi_n^d = d \times \theta_n, \;\; \forall n \in \mathscr{N} \tag{3.10}$$

With,

$$\begin{cases} \theta_n = \dfrac{x_n}{\sum_{n \in \mathscr{N}} x_n} & (3.11) \\ \displaystyle\sum_{n \in \mathscr{N}} \psi_n^d = 1 & (3.12) \end{cases}$$

Equation (3.12) ensures that the sum of the traffic splitting ratios for all the routing planes equals one. In Equation (3.11), x_n indicates what we call the *Divergence Point Level (DPL)*; where the traffic is split in routing plane n. More precisely, if the shortest paths in routing plane n according to the weight system W_n diverge at the gateway, then $x_n = 2$, otherwise $x_n = 1$.

3.4 Simulation Setup

Figure 4.1 shows the chosen simulation scenario that represents a metro access network domain organised in a relaxed-tree (partial mesh) topology. The fixed part of the network is comprised of a hierarchy of nodes, connected by wired Ethernet links. The scenario features 12 Base Stations (BSs) that act as Access Routers (AR). The ARs are interconnected to the single GW by a series of routers, organised in a structure of point-to-point wired links of 100Mbps, apart from the links connected to the GW which are of 1Gbps, so that these links will not create congestion around the GW. All internal links feature the same constant delay of 1 ms.

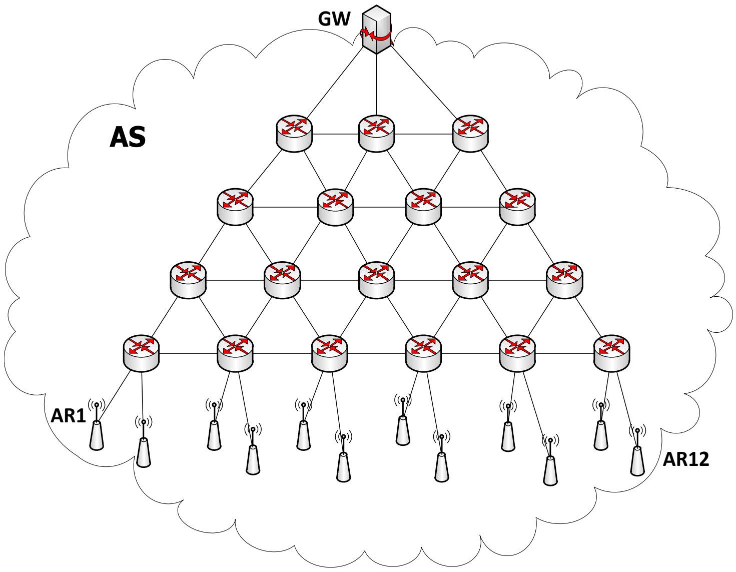


Fig. 3.3 Simulation Scenario. The network depicts an autonomous system comprising 31 nodes and 53 links.

The network also uses *M/M/1* queues in each node. The traffic model used for the simulation is based on [63] and is shown in Figure 3.4, where the aggregated traffic demand at an AR peaks at 25Mbps. The figure portrays the main application classes used for downlink traffic: streaming (audio entertainment), VoIP, video clips and web.

3.5 Performance Evaluation of MPR Method

In this section we present the simulation results that ensue from the link weight assignment and path diversity maximisation processes. The simulations were carried out using a numerical analysis. We also used different approaches to compare our results. We used the hop-count shortest path method ("Hop-Cnt") and we also show the result of the "InvCap" strategy (setting link weights proportional to inverse capacity). Figure 3.5 depicts the evolution of the MLU

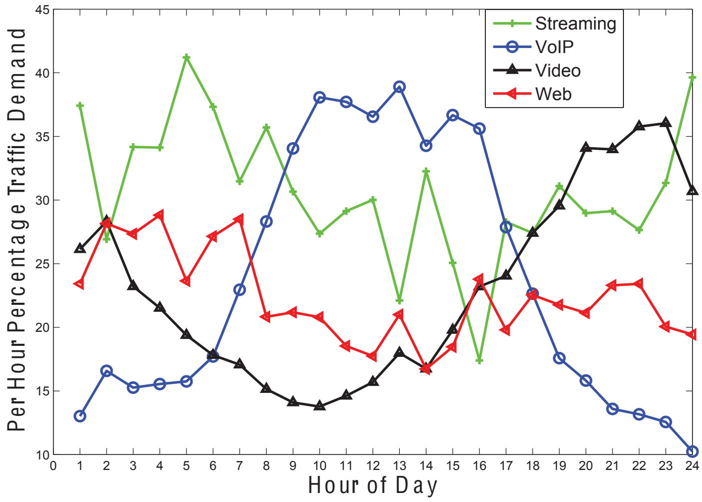


Fig. 3.4 Simulation traffic model - Per hour percentage traffic demand.

and as we can see, our MPR method outperforms both Hop-Cnt SP and InvCap methods.

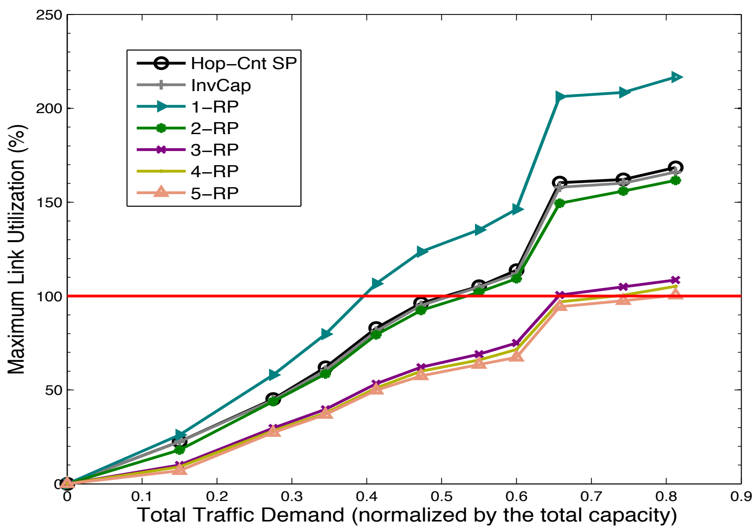
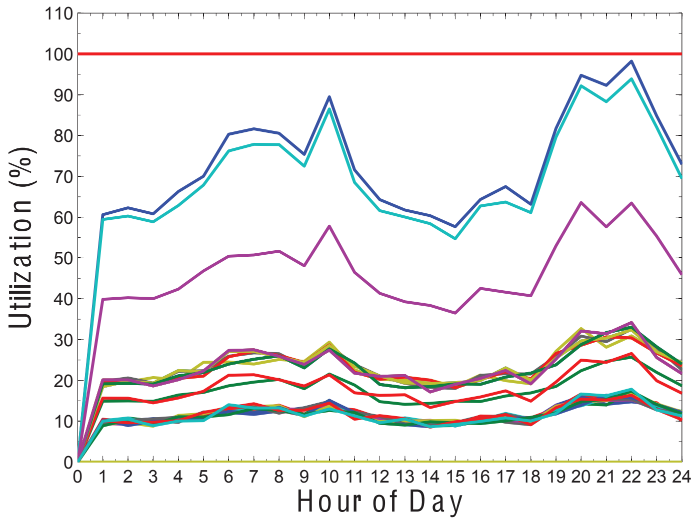


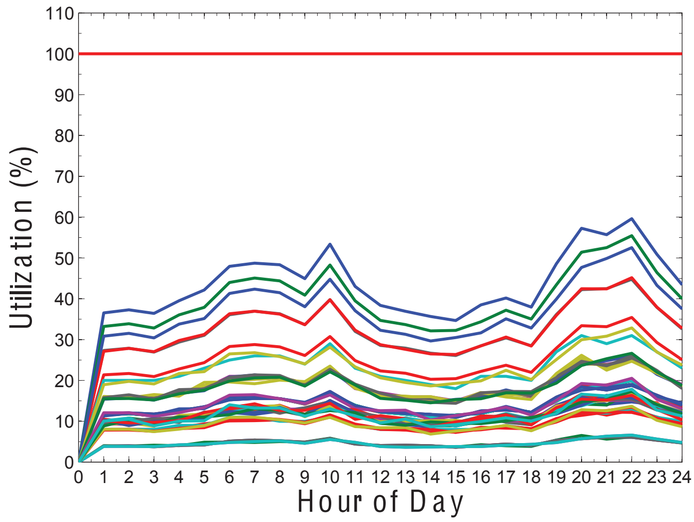
Fig. 3.5 MLU in simulation scenario.

It can also be observed that using one RP provides poorer results than OSPF as traffic is restrained to use specific paths. However, using more than two RPs decreases the MLU by a considerable margin. After three RPs, improvements become less discernible, only lowering the MLU by a couple of percents (see

Table 5.1). Tables 5.1 and 4.3 exhibit in details link utilisations and delays (between the GW and ARs) when the total traffic demand is half the total network capacity. We also show the performance of our algorithm for the utilisation of all the links in the network by comparing OSPF (Hop-Cnt) and MPR with 5 RPs (see Figure 3.6).



(a) OSPF (Hop-Count)



(b) MPR with 5 RPs

Fig. 3.6 Link loads against hour of day.

Table 4.3 indicates the gain in terms of MLD for the different routing schemes. MPR with one RP still performs poorly, but when we use $RP = 5$, we a gain in MLD of over 90% against hop-count OSPF, and a gain in MLU of 40%. The max link delay (Table 4.3) when we use one routing plane is relatively considerable; this is due to the *M/M/1* queueing system. When the link load approaches full capacity, the link delay tends to infinite. Instead, we set the value for link utilisations greater than 100% to 99.99%. This way, link delays do not go to infinite but have a very high relative value which is equivalent to timeout (lost) packets. It is also worth observing the *min*, *mean* and standard deviation of the link utilisation and link delay.

Table 3.1 Link utilisation (%) comparison between the different schemes.

	Max	Min	Mean	StDev
Hop-Count	98.70	16.68	22.32	16.04
InvCap	98.00	16.89	21.60	15.39
1-RP	126.90	7.84	30.84	26.57
2-RP	95.77	26.79	22.80	16.08
3-RP	64.98	21.43	19.02	12.16
4-RP	62.20	19.97	16.96	10.66
5-RP	59.27	3.26	15.81	9.20
Gain (%)	39.95	58.44	29.18	42.65

Table 5.1 shows that these values are also reduced, which is important as far as the overall network performance is concerned. In particular, not only the mean link utilisation and mean link delay are lessened, but also the standard deviation. This means that the values tend to be closer to the mean with MPR than that of OSPF (see Tables 5.1 and 4.3).

Table 4.3 shows the results confirming what earlier studies showed, namely that $3-5$ routing planes are sufficient to achieve good overall network performance. It should be noted that MPR is easily implementable since it is based solely on OSPF and its extensions and the extra overhead produced by MPR is only 1 or 2 bits in IP header. Remember that mapping traffic to routing planes

Table 3.2 Link delay (ms) comparison between the different schemes.

	Max	Min	Mean	StDev
Hop-Count	51.38	1.56	1.25	1.95
InvCap	50.44	1.36	1.19	1.24
1-RP	857.26	1.56	10.48	87.59
2-RP	20.38	1.03	1.20	0.80
3-RP	2.136	0.969	1.133	0.185
4-RP	2.136	0.969	1.133	0.185
5-RP	1.758	1.101	1.130	0.117
Gain (%)	96.58	29.25	6.03	93.99

can be carried out by using the ToS/DSCP field in IP headers (for more details, see [36]). Finally, the routing planes are not constructed dynamically, which avoids periods of traffic instability and flooding overhead, but pre-computed by the network operator on a day-to-day basis.

3.6 Concluding Remarks

In this chapter we introduced Multi-Plane Routing as a routing paradigm for all-IP future access networks. We argue that next generation access networks will be exclusively IP-based, and towards this end, the need for a resilient, efficient and easily implementable routing mechanism is required. The main advantage of MPR over link weight tuning solutions is the ability to change the routing in response to traffic dynamics without triggering a link-state re-convergence. Also, MPR does not rely on topology properties such as the capacity of the links in the network, unlike the InvCap method, hence making our proposal more flexible and independent of topological characteristics. With MPR, we showed that MLU and MLD could be reduced by up to 40% and 90% respectively. We also proved that overall network performance could be increased with only a moderate number of routing planes.

There are a few shortcomings though and the MPR strategy needs to be strengthened by the following:

- MPR needs to be topology-independent, meaning that the routing plane construction process should find an optimal set of routing planes independtly of the physical topology.
- The construction of the routing planes should use different approaches, with each approach focused on optimising one criterion, and then select the best performing approach.
- MPR should be responsive to network dynamics, i.e. flows can be short-lived, bursty, with different rates, or delay-intolerant, in a nutshell QoS-aware.
- Last but not least, MPR's performance should be evaluated in a real-time scenario.

All the above items will be presented and discussed in the following chapter, Chapter 4.

Chapter 4

QoS-Aware Multi-Plane Routing

While ever growing multimedia applications such as IPTV and VoIP have become ubiquitous, the need to migrate from the best-effort service model to one, in which service differentiation can be provided, seems inevitable for future Access Network (AN) architectures.

In this chapter, a novel QoS-aware Multi-Plane Routing based traffic engineering approach for future ANs is proposed. The scheme proposes a solution to the shortcomings listed in Chapter 3, whereby it supports two major practical issues, the topology-independence of MPR and the service level agreement requirements.

4.1 Background Overview

In this chapter, we extended our work presented in Chapter 3, in which a link weight assignment algorithm for network planning and a traffic splitting adjustment algorithm have been developed for creating up to five OSPF routing planes on one hand, and then spreading traffic amid them following the rule *same path for same flow.* A routing plane is an instantiation of the standard OSPF routing protocol. In IP access networks with various degrees of topology meshing, optimum number of OSPF routing planes should utilise all links in the network for increased path diversity for forwarding traffic. Hence, the solution is based on OSPF with no major changes to the operation of the protocol, only extensions to support multiple planes in the networks. The solution also relies on network planning and traffic engineering of multiple planes. To our knowledge, quality of service has never been considered using the Multi-Plane Routing (MPR) approach. Also, no routing policy on routing plane selection for a new incoming session, based on real traffic data, has been proposed.

Towards this end, the contribution of this chapter is threefold. First, we imagined an offline algorithm for creating an optimal set of routing planes that is topology independent. The offline algorithm presents a network planning tool for building the planes based on independent distribution of link weights for each plane. This offline algorithm has for sole input the physical topology with the associated link capacities. It is an extension and enhancement to the algorithm presented in Chatper 3 and has been performed under Matlab, this will form part of the network planning phase. Second, we developed a QoS-aware cost function for routing plane state monitoring that we implemented and extended to network simulator NS-2, as well as developing a whole package (enabling MT-OSPF) on top of the basic Link-State module present in NS-2. Third, we created a policy-based routing scheme for access networks, as a traffic engineering tool, that selects the best routing plane for providing QoS to a new user while improving network performance.

4.2 Topology-Independent RP Construction

This section describes the offline algorithm for the routing plane construction. As stated previously in Section 3.3, the ultimate objective is to maximise the diversity in terms of available paths for each GW-AR pair between all routing planes. In order for the algorithm to be effective whatever the input, namely physical topology, we used two baseline tree-shaped topologies, in which the meshing degree took different values, that is the node degree distribution. Indeed, the average node degree will have a direct impact on the algorithm performance as the higher the node degree distribution, the more available paths for each GW-AR pair, hence the more routing planes can be found. The algorithm starts by computing the first plane using the InvCap method proposed by Cisco. Invcap sets the link weights to the inverse of the capacity of the links. Simply, for each link $e \in \mathscr{E}$, $w(1, e) = 1/C_e$. Figure 4.1 shows one of the topologies used for the simulations. Please note that the depicted topology is one of the baseline topologies, to which a different meshing degree is applied to create several sub-topologies. Link capacities are set up depending on the level they belong to. For instance, links connecting the gateway with next-hop nodes belong to one level, which we will call Level 1. Thus, link capacities are randomly generated following a uniform distribution in $[360, 400]$ for Level 1, $[200, 240]$ for Level 2, $[140, 180]$ for Level 3 and $[60, 100]$ for Level 4 in topology 1. Topology 2 comprises five levels, therefore, link capacities are generated in the following intervals: $[360, 400]$ for Level 1, $[160, 200]$ for Level 2, $[110, 150]$ for Level 2 and 3, and finally $[50, 90]$ for Level 5.

In our approach, we distinguish between the default plane which is the standard flat OSPF network topology where all the links can be used for carrying traffic and the routing planes where a set of links are excluded from the routing process. Three rules are used in the algorithm, they are listed below:

1. Each link must not be used for routing in at least one routing plane.

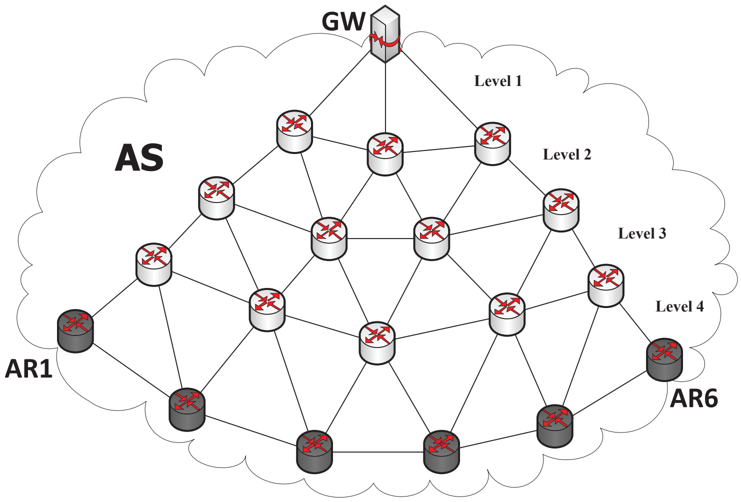


Fig. 4.1 Instance of one of the sub-topologies for Topology 1 used in simulations.

2. All planes are connected which means, in each plane, there is a valid route for each gateway (GW)-Access Router (AR) pair. All nodes in between are considered transit routers, they are not traffic sources or sinks.

3. Each link is used in at least one plane. This property ensures maximum path diversity.

Figure 4.2 sums up the offline process for finding and constructing the optimal set of routing planes. In order to create the optimal set of routing planes for each topology, three methods are used. As mentioned above, a first plane is created, RP 1, whose link weight setting is calculated using the inverse of the capacity of all the links in the network. Obviously, one plane is not enough to satisfy all three rules, so a new plane needs to be found. The design of a new plane is based on finding a link weight configuration. Three methods for computing the link weights are used.

Method 1 *Iterative plane construction*

The method determines the cost of each link to create a new plane. The cost takes into account the inverse of the link capacity, the averaged link cost of the

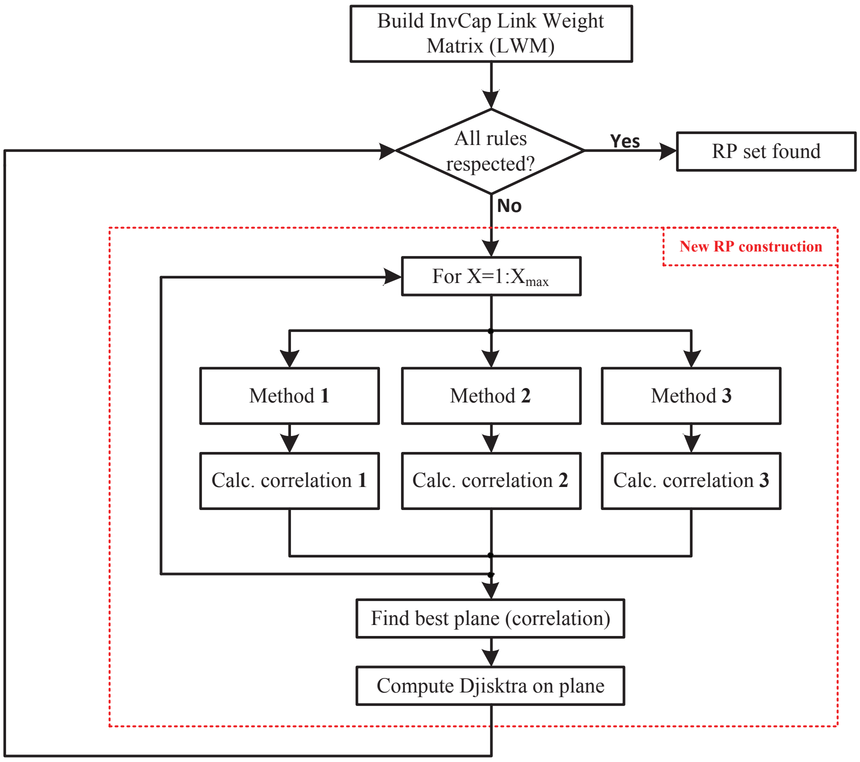


Fig. 4.2 State diagram of the offline RP construction algorithm.

$N-1$ planes, and a third argument.

$$w_n(e) = \frac{\max\limits_{e\in\mathscr{E}}(C_e)}{C_e} + \frac{1}{N}\sum_{n=1}^{N-1} w_n(e) + \alpha_e(n).X \tag{4.1}$$

With $\forall e \in \mathscr{E}$, $\forall n \in [1, N-1]$. X is a multiplicative parameter that is used to vary the granularity of the method; that is, the higher the value of X, the more routing planes will be tested. X ranges from 1 to X_{max} by step of 1, with $X_{max} = \{2;\ 4;\ 8;\ 16;\ 32;\ 64\}$. α_e is defined as follows:

$$\alpha_e(n) = \begin{cases} 1, & \text{if link } e \text{ is included in a path in RP } n-1; \\ 0, & \text{otherwise.} \end{cases}$$

Method 2 *Link degree of involvement*

Unlike Method 1 that only considers the involvement of a link in RP $N-1$, Method 2 considers the involvement of a link e in all RP $n \in [1, N-1]$. The link cost for Method 2 is defined as follows:

$$w_n(e) = \frac{\max\limits_{e \in \mathscr{E}} (C_e)}{C_e} + \frac{1}{N} \sum_{n=1}^{N-1} w_n(e) + \beta_e(n).X \tag{4.2}$$

With $\forall e \in \mathscr{E}$, $\forall n \in [1, N-1]$ and with $\beta_e(n) = \sum\limits_{n=1}^{N-1} \alpha_e(n)$.

Method 3 *Max link degree involvement per GW-AR pair*

Method 3 is basically a sub-set of Method 2, where the cost of a link e that is the most used in one RP is penalised.

$$w_n(e) = \frac{\max\limits_{e \in \mathscr{E}} (C_e)}{C_e} + \frac{1}{N} \sum_{n=1}^{N-1} w_n(e) + \gamma_e(n).X \tag{4.3}$$

With $\forall e \in \mathscr{E}$, $\forall n \in [1, N-1]$. $\gamma_e(n)$ penalises the cost of the link that is the most used in all routing planes $N-1$ for each GW-AR pair. And $\gamma_e(n) = \max\limits_{d \in \mathscr{D}} \left(\sum\limits_{n=1}^{N-1} \alpha_e^d(n) \right)$.

Note that the value of N changes every time a new routing plane has to be found in order to satisfy the three aforementioned properties. For instance, the value of N is equal to 1 when the algorithm starts and builds the first RP based on the InvCap method, then $N = 2,\ 3,\ ...$ until a minimum set of routing planes that satisfy all three rules is found. In order to select the best plane, in terms of maximum path diversity, among all tested routing planes, we use the Pearson product-moment correlation coefficient. After finding a new plane, the algorithm calculates the correlation of the new plane n and the previously constructed ones, $n-1$ planes, with the physical topology that we denote N_0. We chose not to calculate the correlation between RPs two by two as one RP can be uncorrelated with a second one, and a third RP can present a high correlation with the first one. All RPs are compared with the physical topology which never changes. Let $\hat{\mathscr{N}} \subseteq \mathscr{N}$ be a subset of the optimal set of routing planes. Therefore, the Pearson coefficient can be expressed as follows:

$$\begin{aligned} \zeta_{\hat{\mathscr{N}},N_0} = \mathrm{corr}(\hat{\mathscr{N}}, N_0) &= \frac{\mathrm{cov}(\hat{\mathscr{N}},N_0)}{\sigma_{\hat{\mathscr{N}}}\sigma_{N_0}} \\ &= \frac{E\big[\big(\hat{\mathscr{N}}-\mu_{\hat{\mathscr{N}}}\big)\big(N_0-\mu_{N_0}\big)\big]}{\sigma_{\hat{\mathscr{N}}}\sigma_{N_0}} \end{aligned} \tag{4.4}$$

After calculating the correlations for the three methods, we have therefore three contending routing planes. This process is then iterated in the loop taking values from 1 to X_{max} by step of 1. Once X_{max} is reached, the offline algorithm computes the minimum, mean and standard deviation of all calculated correlations for all three methods and select the plane with the lowest correlation; the lowest correlation ensures the number of routing planes is kept to a minimum while ensuring path diversity; Djisktra's algorithm is then performed to compute the paths on the selected routing plane based on the link weight configuration taken from the method. The algorithm stops when a minimum set of routing planes satisfy all three properties.

4.3 Introducing QoS awareness

In this section, we integrate QoS awareness to the MPR mechanism for traffic engineering. This section describes how routing planes are monitored and how the routing plane selection is performed.

4.3.1 Multi-Constrained Plane

The network is constructed to support a set $\mathscr{U}$ of U ($\mathscr{U} : u = 1, ..., U$) users. For simplicity, let N^u be the paths in all routing planes for user u (demand d). For every u, we define an $N^u \times 1$ vector $\pi^{u,d}$ with the rate $\pi_n^{u,d}$ of user u

using RP n as the uth entry of $\pi^{u,d}$. The total rate of user u is denoted $\|\pi^u\|$. Let a $\sum_u N^u \times 1$ vector π^d represent the total bandwidth request at an access router for demand d:

$$\pi^d = \left[(\pi^1)^T \ (\pi^2)^T \ \cdots \ (\pi^U)^T\right]^T \tag{4.5}$$

Finally let π be the total aggregated traffic in the network and it is expressed as $\pi = \sum_d \sum_u \pi^{u,d}$. We consider the routing planes to be identical for downlink and uplink however they can be selected differently for downlink and uplink. Also, a stream of packets belonging to the same session will follow the same path (same RP) for session request and transfer of actual data.

Each access router has a utility function U^d as a function of its aggregate demand $\sum_u \|\pi^{u,d}\|$. The basic multi-plane routing problem is to maximise the network resources by allocating a specific routing plane, that is a specific path, for each user u of rate $\|\pi^u\|$ subject to link capacity constraints. Let $\|\pi^{u,d}\|_0$ be the number of non-zero entries of $\pi^{u,d}$. Then the multi-plane problem can be formulated as a non-convex optimisation problem:

$$\begin{aligned} \max_{\pi \geq 0} \quad & \textstyle\sum_d U^d(\|\pi^{u,d}\|), \ \forall d \in \mathscr{D} \\ \text{s.t.} \quad & R\pi \leq c \\ & \|\pi^{u,d}\|_0 = 1, \ \forall u \in \mathscr{U}, \ \forall d \in \mathscr{D}. \end{aligned} \tag{4.6}$$

Bandwidth constraint Let a path p_n^d be represented as a concatenation of successive links, and $p_n^d = \{e_{ij,n} \mid \forall i \neq j, \ (i, \ j) \in \mathscr{V}^2, \ \forall d \in \mathscr{D}, \ \forall n \in \mathscr{N}\}$. We denote by $b(e_{ij,n})$ the available bandwidth on edge e_{ij} for demand d in RP n. Therefore the available bandwidth of the path p_n^d in RP n for demand d is:

$$b(p_n^d) = \min_{e_{ij,n} \in p_n^d} b(e_{ij,n}) \tag{4.7}$$

We note c_b the QoS bandwidth constraint for the session. Then the bandwidth requirement is expressed as:

$$b(p_n^d) \geq c_b \tag{4.8}$$

Bandwidth is a non-additive QoS parameter, therefore it is easily dealt with a pre-processing phase by pruning all paths that do not satisfy the QoS requirements for the session [64].

Additive constraints As discussed in prior sections, considering just one QoS constraint at a time is not sufficient to provide QoS guarantees to all kinds of applications, especially ever-increasing Internet multimedia applications. Thus we propose to use the principle of multi-constrained path or MCP QoS routing [65] based on multiple QoS metric to find a feasible path (routing plane) for each GW-AR pair. Each application has different service-level requirements, some are delay-, jitter- and/or reliability-sensitive applications, thus, this approach can provide more on-demand and dynamic support for all types of traffic.

Each link $e_{ij,n}$ in path p_n^d is associated with K additive QoS metrics $m_k(e_{ij,n})$, where $k \in \kappa$ $(\kappa : k = 1,\ 2, \ldots,\ K)$. There are also K constraints c_k^t, $\forall t \in \tau$, where τ $(\tau : t = 1,\ 2, \ldots,\ T)$ is the set of traffic types. The MCP problem is to find RP n for demand d, that is between access router r and the gateway, that satisfies the following requirement:

$$m_k(p_n^d) \equiv \sum_{e_{ij,n} \in p_n^d} m_k(e_{ij,n}) \leq c_k^t,\ \forall k \in \kappa \tag{4.9}$$

without cost optimisation (primary cost of feasible path p_n^d in routing plane n satisfying requirement (4.9) is not necessary to be minimised).

The non-linear cost function [66], [65] shown in (4.10) illustrates the method to nonlinearly combine additive QoS parameters, such as delay, jitter, reliability, packet loss, into a single cost metric for any path p_n^d in routing plane n for demand d while the non-additive ones such as bandwidth, as stated previously, is easily dealt with a pre-procession step. Let Γ ($\Gamma : \gamma = \gamma_0,\ \gamma_1, \ldots,\ \gamma_k$) be the set of weights used for each constraint k. Therefore, the cost function for any path p_n^d for demand d in routing plane n is expressed as follows:

$$\begin{aligned} \varphi_\Gamma^t(p_n^d) &\equiv \left(\tfrac{m_1(p_n^d)}{c_1^t}\right)^{\gamma_1} + \left(\tfrac{m_2(p_n^d)}{c_2^t}\right)^{\gamma_2} + \ldots + \left(\tfrac{m_k(p_n^d)}{c_k^t}\right)^{\gamma_k} \\ &= \sum_{i=1}^{k} \left(\frac{m_i(p_n^d)}{c_i^t}\right)^{\gamma_i} \end{aligned} \tag{4.10}$$

with $\forall d \in \mathscr{D},\ \forall n \in \mathscr{N},\ \forall t \in \tau$ and $\gamma_i \in [0,\ 1]$.

As mentioned above, φ_Γ^t is a cost function weighted by the set Γ. The γ_i variables allow to give more priority to specific QoS parameters than others, for instance, certain multimedia applications require drastically low delay or jitter but may be more tolerant to packet loss.

4.3.2 Plane Selection Policy for Q-MPR

Though the proposed QoS-aware multi-plane routing scheme allows an incoming session to be routed along a certain routing plane that respects the service level agreements for the session, it does not yet guarantee that the load is optimally balanced within the network, and hence network is not well utilised. In order to ensure that low QoS traffic is routed through lesser congested paths away from the paths in routing planes used by greedy QoS sessions, we propose a plane selection (PS) policy. PS policy has been enforced to ensure traffic within the network is regulated and routed appropriately [67]. The aforementioned routing policy needs to be implemented in the border routers within the network, namely the access routers and the gateway. This policy assures that a routing plane is selected by these border routers according to the class of traffic an incoming packet belongs to. We assume that the edge routers possess similar capabilities to that of bandwidth brokers in the framework of DiffServ, that is they have the knowledge of incoming flow's QoS requirements based on the DSCP value for instance.

To derive the routing policy we define extra notations. Let χ be the subset of routing planes ($\chi \subseteq \mathscr{N}$) that support the quality of service required by the session. Therefore, we denote $\overline{\chi} \subseteq \mathscr{N}$ the complementary set of χ which denotes the routing planes that do not provide QoS guarantees for a new incoming session. Note that $\chi \cup \overline{\chi} = \mathscr{N}$. In the case where several routing planes respect the SLRs for the session, one still has to be selected. Towards this end, we add an extra parameter in Equation (4.10) that checks the available bandwidth after considering the current throughput request of a new session. Thus, Equation (4.10) becomes:

$$\varphi_{\Gamma}^{t}(p_n^d) \equiv \sum_{i=1}^{k} \left(\frac{m_i(p_n^d)}{c_i^t} \right)^{\gamma_i} + \left(\frac{b(p_n^d) - \|\pi^{u,d}\|_0}{C(b(p_n^d))} \right)^{-1} \tag{4.11}$$

With $\forall d \in \mathscr{D}$, $\forall n \in \mathscr{N}$, $\forall t \in \tau$ and $\gamma_i \in [0,\ 1]$.

Note that $C(b(p_n^d))$ represents the capacity of the link $e_{ij,n} \in p_n^d$ that has the least available bandwidth on the path in routing plane n for demand d. Equation (4.11) allows the AR to select the least congested routing plane, i.e., the one that presents the highest available bandwidth after taking into account the required throughput of the new session request. The overall decision making process is depicted in Algorithm 2 which presents the overall plane selection policy for the Q-MPR mechanism.

When a packet arrives at an AR r, the policy routing procedure is performed. If the session is admitted into the network, AR r verifies which traffic class the incoming session belongs to and obtains SLRs for that particular traffic class (shown in Table 4.3). The AR discards all RPs that do not satisfy the QoS constraints; at that point we know there is at least one RP that can be

Algorithm 1 Plane Selection Policy

procedure POLICY-PS $(P_n^d, \tau, \kappa, \mathscr{N}, V)$
    Packet arrives at AR $r \in \mathscr{V}$ destined to gateway $g \in V$
    if $\|\pi^{u,d}\|_0 \leq b(p_n^d)$, for at least one $n \in \mathscr{N}$ **then**
        Session is admitted
        Perform lookup and check traffic class $t \in \tau$
        Obtain QoS requirements c_k^t for traffic class t
        Prune all RPs in $\mathscr{N}$ that do not satisfy SLRs for each $k \in \kappa$ and retrieve set χ.
        Calculate cost for each RP $x_i \in \chi$
$$\varphi_\Gamma^t(p_{x_i}^d) = \sum_{i=1}^{k} \left(\frac{m_i(p_{x_i}^d)}{c_i^t}\right)^{\gamma_i} + \left(\frac{b(p_{x_i}^d) - \|\pi^{u,d}\|_0}{C(b(p_{x_i}^d))}\right)^{-1}$$
        Select RP x_1 with lowest cost φ_Γ^t for the session of user u so that
$$\varphi_\Gamma^t(x_1) \leq \varphi_\Gamma^t(x_2) \leq \ldots \leq \varphi_\Gamma^t(N - \overline{X})$$
    else Reject session
    end if
end procedure

selected for carrying the session. Set χ is retrieved, and the cost is calculated for each RP in χ. The RP presenting the lowest cost φ_Γ^t is selected.

4.4 Simulation Setup and Performance Evaluation

How well can our new Q-MPR scheme perform, and how fast can the optimal set of routing planes (RPs) be? In this section, we compare the performance of the Q-MPR mechanism against currently deployed link-state routing protocols, OSPF, Cisco's InvCap and our basic MPR method, with no routing plane selection policy based on QoS.

4.4.1 Offline algorithm

This subsection details and evaluates the performance obtained by the offline procedure of constructing an optimal set of routing planes. The simulations are performed with Matlab for the offline algorithm and comprise eleven different topologies. We generate two main topologies in which we use a different meshing degree, spanning from a strict tree sub-topology to an almost full-meshed topology. Table 4.1(a) presents the setup of all the eleven topologies used for simulations. "$TxMy$" indicates the topology number and the degree of meshing. The higher y, the higher average node degree distribution, and hence the more paths will be available between each GW-AR pair. $T1M1$ and $T2M1$ are sub-topologies of Topology 1 and Topology 2 where only one path is available for carrying traffic for each GW-AR pair.

(a) Setup of the topologies

Topo	# Nodes	# ARs	# Links	Total capacity (Gb)
T1M1	19	6	18	7.84
T1M2	19	6	32	11.94
T1M3	19	6	36	12.98
T1M4	19	6	39	14.06
T1M5	19	6	41	15.34
T2M1	32	14	31	9.84
T2M2	32	14	53	15.28
T2M3	32	14	59	16.48
T2M4	32	14	61	16.88
T2M5	32	14	65	18.00
T2M6	32	14	67	18.40

(b) Output of the offline algorithm

Topo \ X	2	4	8	16	32	64
T1M1	1	1	1	1	1	1
T1M2	-1	-1	-1	5	4	4
T1M3	-1	-1	-1	7	7	5
T1M4	-1	-1	-1	5	6	4
T1M5	-1	-1	-1	5	6	5
T2M1	1	1	1	1	1	1
T2M2	-1	9	6	4	3	3
T2M3	-1	-1	-1	5	5	4
T2M4	-1	-1	-1	6	7	4
T2M5	-1	-1	-1	8	6	5
T2M6	-1	-1	-1	-1	5	5

Table 4.1 Offline setup and performance.

Table 4.1(b) shows the output of the offline algorithm, that is the number of RPs found to form an optimal set on a per topology basis. Different values

Tech / Topo	OSPF	InvCap	MPR					
			X=2	X=4	X=8	X=16	X=32	X=64
T1M1	0.0129	0.0179	0.158	0.224	0.169	0.138	0.137	0.143
T1M2	0.0175	0.016	0.259	0.352	0.540	0.598	0.755	1.080
T1M3	0.0121	0.0116	0.251	0.358	1.057	0.861	1.354	1.495
T1M4	0.0118	0.0172	0.252	0.455	0.518	0.707	1.194	1.142
T1M5	0.012	0.0126	0.560	0.373	0.518	0.641	1.120	1.511
T2M1	0.0753	0.0771	0.297	0.371	0.291	0.292	0.308	0.286
T2M2	0.0851	0.0745	1.081	1.680	1.359	1.203	1.612	2.131
T2M3	0.0785	0.0751	1.437	1.393	2.025	1.599	2.424	3.060
T2M4	0.0734	0.0756	1.074	1.280	1.926	2.540	3.439	2.975
T2M5	0.1032	0.076	1.093	1.286	1.908	3.082	2.114	3.897
T2M6	0.0779	0.076	1.253	1.285	1.792	3.009	2.387	4.781

Table 4.2 Offline algorithm complexity, running time (s)

of X have been studied, and Table 4.1(b) clearly indicates that for a value of 64, generally an optimal set with fewer RPs is found. Recall that an optimal set of RPs is found if the three properties stated in Section 4.2 are satisfied with a minimum number of RPs. A value of -1 denotes that the value of X is not sufficient to provide an optimal set of routing planes. In this case, the value of X is increased to the next value, and the process starts over. Note that 1 routing plane could be found for $T1M1$ and $T2M1$ as these two topologies are strict trees, therefore only one path is available between each access router and gateway pair. Among all values of X tested, the set with the fewest number of routing planes is selected, this is to ensure minimum implementation and routing table maintenance overhead. However, with a higher number of planes, more paths are available and thus one can assume that traffic can be better balanced. We will show in Subsection 4.4.2 that this statement is wrong.

The computational complexity, represented by the running time expressed in seconds, is shown in Table 4.2. OSPF and InvCap methods outperform our proposed strategy as only one path is computed for each GW-AR pair. It can also clearly be seen that the higher the value of X, the longer and the more complex the algorithm is. Also, as the topology presents a higher meshing degree, namely more paths are available for each GW-AR pair, the complexity is increased. A maximum value of 64 is shown for X as the algorithm does not perform better for higher values of X.

4.4.2 Online algorithm

In this subsection, the performance of the online algorithm, which takes for input the optimal set of routing planes computed in the offline algorithm, is studied. The routing plane selection and thus the splitting of traffic is directly affected by the output of the RP construction process. The online simulations were run using the well known network simulator NS-2 that we extended to support Multi-Topology OSPF routing, as specified by the IETF [18]. The extensions to NS-2 to support multi-plane routing have been studied by authors in [68, 69]. Different classes of traffic have been used for simulations, each associated with specific QoS requirements or SLRs [70], data rate and session time [63], and are all listed in Table 4.3.

Table 4.3 Traffic types[1] and associated QoS requirements.

Traffic Class	Data Rate	Session Time	QoS requirements		
			Latency	Jitter	Packet loss
Class 1	Low (≈ 150 Kbps)	180 sec	40-65 ms	0.5-2 ms	0.1-0.5 %
Class 2	Medium (≈ 250 Kbps)	300 sec	4-5 s	*none*	5 %
Class 3	Low (≈ 128 Kbps)	200 sec	300-600 ms	2 ms	5 %
Class 4	High (≈ 500 Kbps)	360 sec	300 ms	30 ms	1 %
Class 5	Low (≈ 100 Kbps)	90 sec	*no specific requirement*		

[1] Applications examples; Class 1 : VoIP, Class 2 : streaming video, Class 3 : streaming audio, Class 4 : interactive video, Class 5 : best effort data.

The routing plane configuration drawn from the offline process, which determines the link weight matrix (LWM) for each RP, is computed and constructed in NS-2 . Recall that each routing plane is a subset of the physical topology and each is associated with a separate routing table. A new incoming session is generated randomly among traffic classes shown in Table 4.3. As the simulation runs, traffic is generated with a decreasing session arrival time so as to load the network until congestion level. When a new session request is made at an access router, the latter checks for bandwidth availability on the path(s) to reach the destination, independently of the method used (OSPF, InvCap, MPR or Q-MPR).

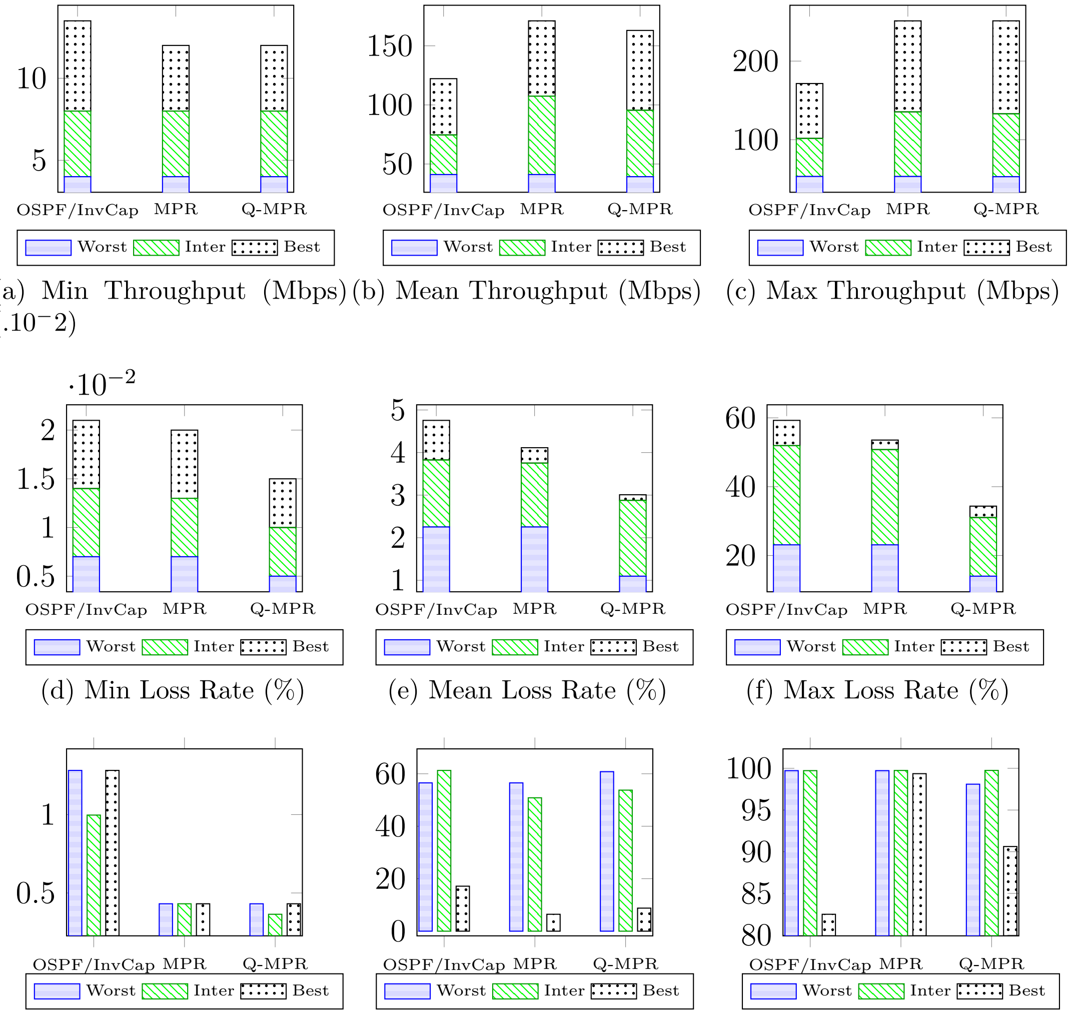
OSPF and InvCap protocols will forward the traffic demand to the destination on the available path. With MPR, several routing planes, hence several paths are available towards the destination node (GW for uplink, AR for downlink). For each new incoming session, a routing plane is randomly selected for routing traffic towards the destination. In Q-MPR, new sessions are forwarded based on the required QoS for the sessions. Planes not satisfying all QoS requirements will be pruned at session arrival. In the case where several RPs satisfy the QoS requirements for the session, the plane with most available bandwidth will be utilised.

Figure 4.3 presents the performance of the four strategies regarding the total received throughput, the overall packet loss rate and the total session blocking rate for $X = 64$, value providing the best results in the offline algorithm (used as the network planning procedure). For each performance metric, we store and show the minimum, mean and maximum value throughout the simulation, for all GW-AR pair and for all planes, and in the worst, medium and best cast scenario (topology).

Open Shortest Path First protocol computes the routes towards all destinations in the network based on the shortest path in terms of number of hops. Link weights are typically set to 1, although a fixed constant different from 1 would produce the same result. The shortest-hop path is used between the gateway and each access router, regardless of the number of available paths towards the destination and the capacity of the path. Only one path will be used for forwarding traffic. With InvCap, which uses OSPF with an improved link weight setting, traffic towards a destination will still be routed along a single path. However, link weights are set to the inverse of the capacity of the link, that is a link with a low bandwidth will be penalised and assigned a high cost so that it will be avoided for path calculation. In other words, unless no other paths including this link is available, a link with a low capacity will be avoided. Traffic in InvCap therefore uses paths that are not necessarily shorter in terms of hop count, but more able to handle the amount of traffic. For lack of space, we could not present the limited differences in performance between OSPF and InvCap for these particular topology family (tree-like) but we noted the following. The minima are lower in InvCap than in OSPF. Maxima and mean values are identical, this is explained by the fact the topology are tree-like, and traffic is solely flowing between the gateway and access routers. As the network becomes overloaded, and because only path is available for each source-destination pair, the performance in both strategies is similar. It can clearly be noticed that, although InvCap offers better performance in transit or core networks compared to OSPF, it does not outperform OSPF in access networks. For these reasons, we decided to group OSPF and InvCap together in the performance graphs in the rest of the chapter.

With MPR, multiple routes are available between every GW-AR pair, as many routes as the number of routing planes. This has two consequences: first, traffic can be split over several paths, hence balancing the load within the network. This leads to increasing the overall throughput in the network and hence decreasing the blocking probability. Second, as shortest-hop routes are no longer used, higher delays are experienced by the sessions forwarded onto the RPs. In Q-MPR, for every new incoming session, the best plane, namely the best path, is selected for routing the session towards its destination based on the QoS requirements and the state of the plane. This will directly affect the blocking rate as more sessions will be denied access for lack of available paths. Blocking rate in Q-MPR is increased by 26% in the worst case compared to basic MPR strategy. Despite this effect, we denote that the overall throughput remains unchanged compared to MPR and presents a maximum gain of 45.2% compared to OSPF/InvCap schemes. It is explained by the fact that better paths are used for carrying traffic, the packet loss rate is lower in Q-MPR, with a maximum gain of above 75% compared to MPR and 85.9% compared to OSPF/InvCap. The end-to-end delay presents slightly lower values in Q-MPR compared to MPR in Topology 1, with a maximum gain of 61.6%.

In details, Figure 4.3 depicts values for all metrics in a stacked-column structure, making it easy to compare performance across the studied approaches. Figure 4.3(a), (b) and (c) show the total received throughput in Mbps; here the higher the value, the better. Looking at Figure 4.3(b) , the mean throughput in the best scenario for Q-MPR (68 Mbps) is higher than that of MPR (63 Mbps), and OSPF/InvCap (47 Mbps). This becomes even more obvious by looking at Figure 4.3(c). Figure 4.3(d), (e) and (f) show the packet loss rate; here the smaller the value, the better performance. (d) and (f) show clearly that Q-MPR outperforms OSPF/InvCap and the QoS unaware MPR. In Figure 4.3(f), Q-MPR in the intermediate sample topology presents a maximum loss rate of 17%, while MPR and OSPF/InvCap show higher values of 27% and 28% respectively. Looking at the minimum, average and maximum values enable us to assess the performance as not only the extreme values but also the median values are shown. Thus, one can draw a realistic picture of how the network is behaving.



(a) Min Throughput (Mbps) (b) Mean Throughput (Mbps) (c) Max Throughput (Mbps) $(.10^{-}2)$

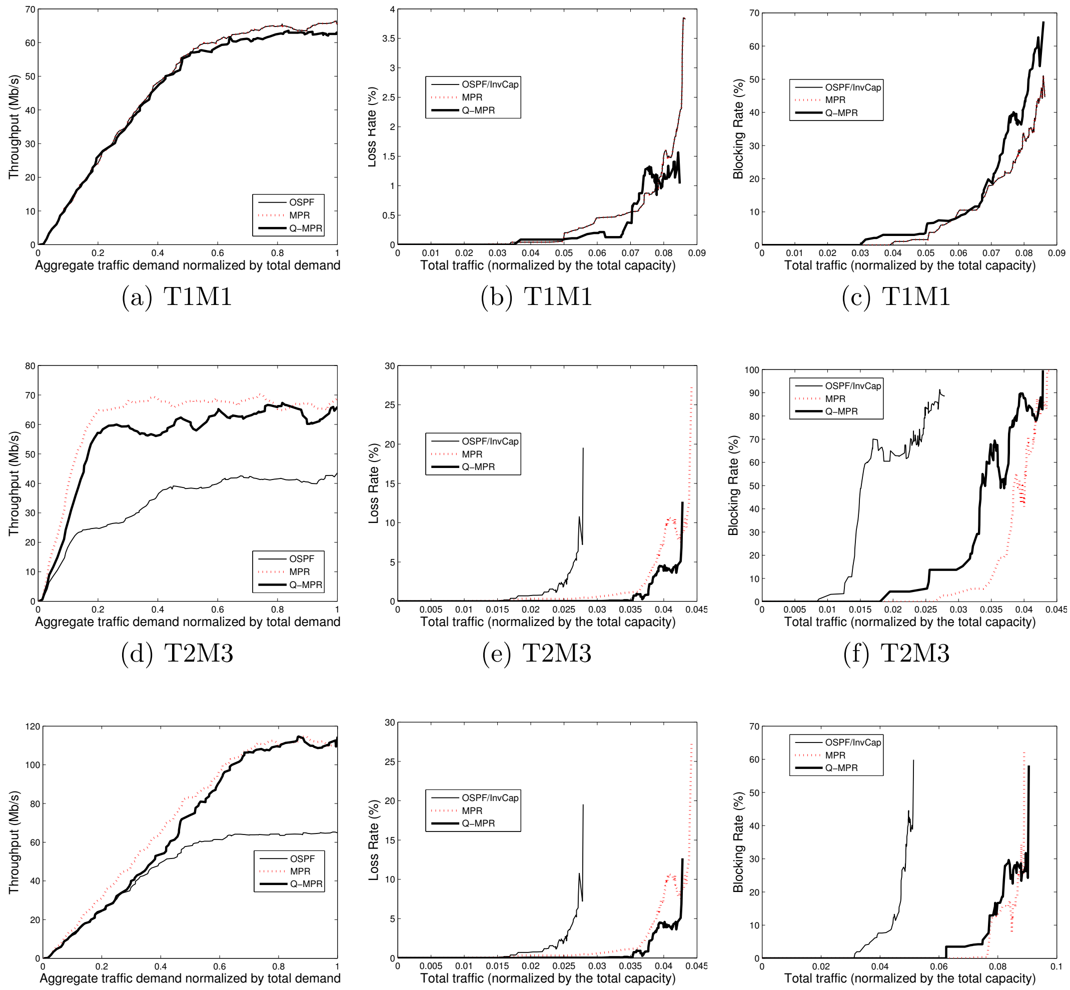
(d) Min Loss Rate (%) (e) Mean Loss Rate (%) (f) Max Loss Rate (%)

(g) Min Blocking Rate(%) (h) Mean Blocking Rate(%) (i) Max Blocking Rate(%)

Fig. 4.3 Total throughput, loss rate and blocking probability (min, mean, max) for worst, intermediate and best case scenarios. X = 64.

Figure 4.4 and Figure 4.5 depict the performance of the studied strategies in the worst case, that is only one physical path is available for each GW-AR pair, in an intermediate case and in the best case, where the node degree is higher, as we increase progressively the total network load (normalised by the total network capacity). Q-MPR and MPR outperform OSPF and InvCap. For $X = 32$, Topology $T1M1$ presents the worst performance, OSPF/InvCap, MPR and Q-MPR perform similarly. Recall that in Topology $T1M1$ traffic can be routed only on one path. Therefore, only one routing plane is available in MPR and Q-MPR, downgrading their performance to that of OSPF and InvCap methods. The best case is shown with Topology $T1M3$, we note that with Q-MPR and MPR a higher amount of traffic can be carried in the network (see Figure 4.4(g)). It can also be seen that OSPF/InvCap present a worse total packet loss rate and session blocking probability (see Figure 4.4(e), (f), (h) and (i)). Finally, in Figure 4.3(g), (h) and (i), the blocking probability, expressed in percentage, indicates the ratio of blocked sessions over the total number of incoming sessions. Q-MPR shows greater performance for the lower bound values but its performance decreases for average and maximum. OSPF will tend to block sessions as routing engine will not find paths with sufficient bandwidths to route traffic, however Q-MPR will block sessions as it is more constrained. Hence the little gap in the blocking probability for average and maximum.

For $X = 64$, results are analysed for the four strategies, and the worst case (Topology $T2M1$, Figure 4.5(a), (b) and (c)), intermediate case (Topology $T2M4$, Figure 4.5(d), (e) and (f)) and the best case (Topology $T1M4$, Figure 4.5(g), (h) and (i)) are shown. From Figure 4.5(h) and (i), it can be seen that Q-MPR perform better than its counterparts MPR, OSPF and InvCap for $X = 64$ than that of $X = 32$. Indeed, in Figure 4.5(h), losses occur for a higher total traffic; 7% for Q-MPR with $X = 64$ against 3.5% with $X = 32$. Similarly,



(a) T1M1 (b) T1M1 (c) T1M1

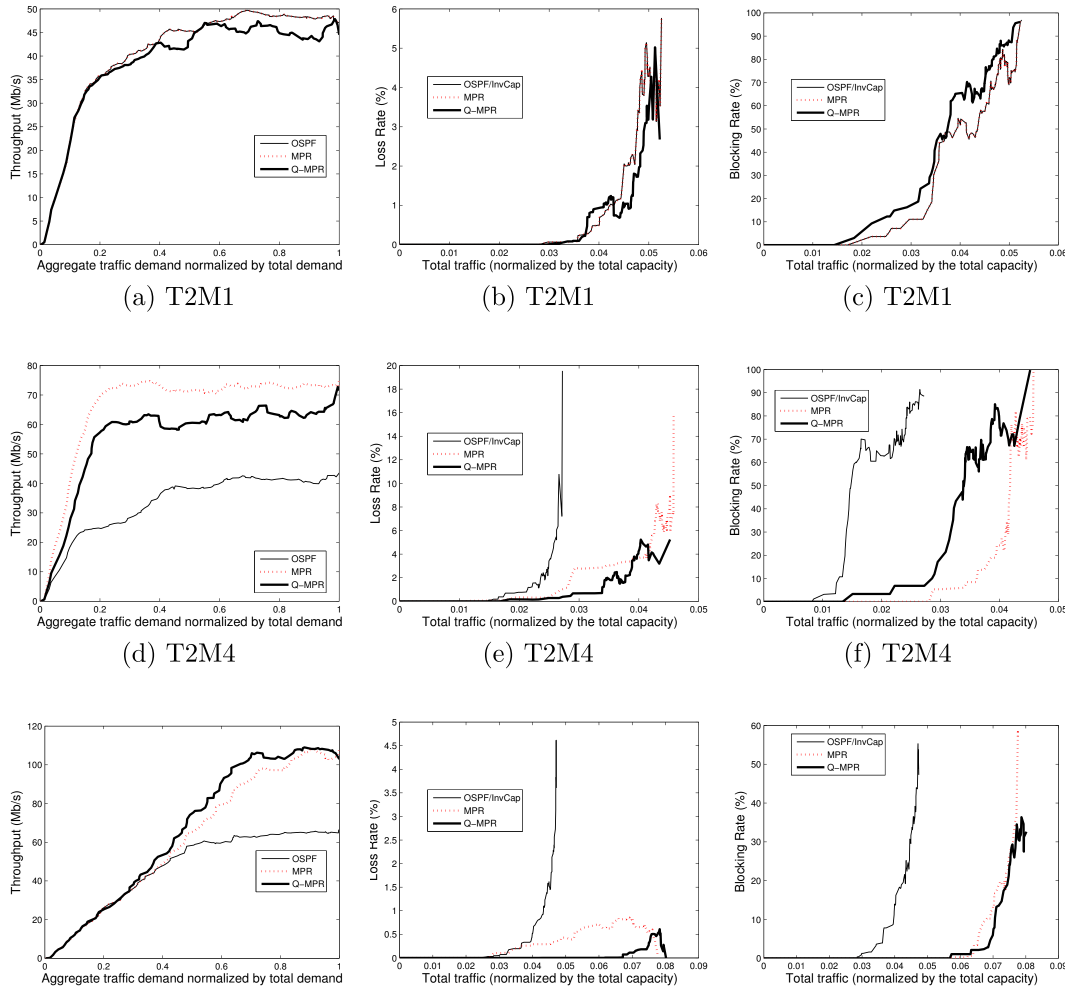
(d) T2M3 (e) T2M3 (f) T2M3

(g) T1M3 (h) T1M3 (i) T1M3

Fig. 4.4 Total received throughput, packet loss rate and session blocking rate, X = 32.

the total session blocking rate is slightly better in Q-MPR with $X = 64$ than with $X = 32$ (see Figure 4.5(i) and Figure 4.4(i)).

We demonstrated in this section that despite a fewer number of routing planes with $X = 64$ than with $X = 32$, better performance is achieved as more routing planes are tested in the offline algorithm, hence a better set of RPs can be found.



(a) T2M1 (b) T2M1 (c) T2M1

(d) T2M4 (e) T2M4 (f) T2M4

(g) T1M4 (h) T1M4 (i) T1M4

Fig. 4.5 Total received throughput, packet loss rate and session blocking rate, X = 64.

4.5 Concluding Remarks

Building access networks' routing and traffic engineering via extensions proposed in the thesis have shown to enable significant improvements in path diversity compared to standard IP routing. The extensions required in IP routers running OSPF for implementing the MPR method are comparable to the alternative solutions, both in the performance and flexibility. However, an analysis on the overhead and stress incurred on edge-routers and the comparison to that of MPLS should be included in future work in a real-world scenario. In the IP routing, ECMP could be used for comparison as it is typically applied in some types of topologies, but it is not able to flexibly accommodate for overall path diversity in a high degree of meshing and large number of nodes in IP access networks. On the other hand, MPLS is able to achieve path diversity but the high overhead of its installation and maintenance present a strong case for finding the solutions in IP routing adaptations as proposed in the thesis. This work additionally promotes IP access networks as a natural extension of the infrastructure of the Internet, not requiring additional networking support in the scoped segment of the network that provides access to end-user terminals. In addition, network planning and traffic engineering via QoS-awareness and the algorithms that comprise the MPR method are features that would equally be needed for other networking solutions in IP access networks, e.g. MPLS already uses OSPF for LPS path computations and traffic engineering. QoS-aware MPR allows the network to maintain several independent logical topologies that can be used to balance the traffic load within the network whilst providing QoS for end users. Our method classifies new incoming sessions and routes them at the edge of the network, namely at the gateway and at the access nodes, onto the routing plane that achieves best network performance and that provides best QoS for the user. The method uses both an offline and an online process for network planning and traffic engineering respectively, and the performance issues were addressed both theoretically and by simulation. The results showed clearly our Q-MPR scheme outperforms existing strategies even with a small number of routing planes (5 for high-meshed access networks). Using Matlab and the NS-2 simulator, we compared Q-MPR against basic MPR, OSPF and the InvCap mechanisms. Total received throughput is increased by 45.2% with MPR compared to OSPF and InvCap strategies. Q-MPR, while generally blocking more sessions and using the same routing plane configuration as that of MPR, achieved the same overall throughput whilst lowering the total packet loss rate.

Chapter 5

Proactive Autonomic TE with Mobility Management for Access Networks

In the previous chapters, Chapter 3 and 4, we have introduced a new routing scheme (Multi-Plane Routing) for next generation IP-based access networks based on the widely deployed OSPF protocol. In this chapter, however, we propose a QoS routing solution for PMIPv6-based access networks, where mobility management is incorporated, by selecting optimally a mobility agent on a per-session basis.

The agent micro-mobility protocols, such as Hierarchical Mobile IPv6 (HMIPv6) and Proxy Mobile IPv6 (PMIPv6), have become leading contenders for providing micro-mobility support to Mobile Nodes (MNs). The presence of Mobility Agents (MAs) in these networks can lead to constrained routing and create areas of bottleneck around the mobility agents. When an MA is integrated in the access network all traffic is forced to flow through that MA potentially over-utilising paths along the MA while other paths of the network remain under-utilised. For the efficient deployment of such networks, optimal and robust mobility agent selection and load balancing mechanisms are required. This chapter introduces Proactive Autonomic Load Uniformisation (PALU), a self-managed load balancing scheme in which the congestion caused by MAs is reduced leading to better utilisation of the network resources. Assuming that the network supports multiple MAs, the proposed solution selects the optimal MAs by distributing optimally the incoming load within the network whilst at the same time maintaining the QoS requirements for the MNs. The results show that the congestion is lowered by 25% within the network and the load is distributed uniformly across the MAs.

5.1 System Architecture

This section will introduce the problem and describe the reference network scenario.

5.1.1 Introduction

The rapid growth of Internet networks, increasing demands from end users and new applications, has created a constant need for efficient connectivity, service delivery and network management solutions in those networks. Some of these solutions are in areas of mobility, QoS provisioning, and security as the underlying IP functions in such network. The advances in technology have recently seen the concepts of autonomous computing being adapted to Telecom networks creating a discipline of self-management in network operations [71]. These proposals build on intelligent orchestration of network processes, expediting the operations and reducing the need for human interventions. [72] presented a collective view on the framework for solutions for self-management of Internet access networks in a unified vision towards the Future Internet evolution conducted in the Self-NET project [73]. This constitutes the foundation for the material presented in this chapter. The work in Self-NET is one of the combined efforts in advancing of autonomous network operations including other efforts such as Autonomic NEtwork Management Architecture (ANEMA) [74], Autonomic Network Architecture (ANA) [75] and Generic Autonomic Network Architecture (GANA) [76]. The essence of the proposal is based on fitting the very engine of the self-management network [77], part of that is the control loop features of Monitoring, Decision-making and Execution (i.e. the M-D-E cognitive cycle). Its presence offers novel ways of controlling the operations of network such as its IP protocols suited to the purpose of its engagement. In this chapter we show how self-management can offer improvements in utilisation of network resources via the control of mobility management mechanisms and topological awareness.

5.1.2 Quality of Service Considerations

In the literature, Quality of Service (QoS) has been intensively studied in the context of access networks, and in particular mobility agent based access networks where traffic is forced to flow through these agents. Most QoS protocols and QoS-routing proposals [78, 79] consider discovering a single path that supports a certain QoS requirement (e.g., end-to-end delay, handover delay, signal to noise ratio, data rate, stability of the route, etc.). However, most of the QoS-routing paradigms, and all the aforementioned protocols are reactive routing protocols. These architectures, mostly based on DiffServ mechanisms and a blocking rule on certain links, stop traffic from QoS-classes from flowing over those particular links (e.g., video traffic over a narrow band waveform). This leads to parts of the network being uselessly utilised. In this work, we show that by selecting the appropriate mobility agent for the session at the edge of the network (access router for downlink traffic or gateway for uplink) based on QoS requirements the network can be optimally utilised and resources optimally balanced.

5.1.3 Coupling of Mobility Management and Self-Management

This framework considers Mobile IPv6 [80] for macro-mobility and PMIPv6 with Network Localised Mobility Management (NetLMM) [5, 54] for micro-mobility. PMIPv6 was proposed to minimise the extensive handover latency that exists in Mobile IP by using mobility agents, namely Local Mobility Anchors (LMAs). The LMAs act as an anchor between the Mobile Node (MN) and the Correspondent Node (CN) and as a result minimise the handover delay considerably. Authors in [81, 82] showed that lower total costs could be achieved for their approach than that for HMIPv6 protocol. However, it was shown in [83] that the presence of mobility agents (LMA or MAP) can lead to non-optimal routing and increased congestion in the network. For example, when these local mobility anchors are integrated into an access network the QoS routing is broken into two; from the gateway (GW) to the mobility agent and from the mobility agent to the respective access router, Mobile Access Gateway (MAG) in PMIPv6 networks, to which the mobile node is associated with. This can potentially lead to congestion around the LMAs, under-utilisation of certain parts of the network while the paths along the LMAs are over-utilised. The paradox of mobility management is that placement of mobility agents offers smoother and quicker mobility of hosts but creates congestion within the network.

The added mobility management function, based on the M-D-E cycle, is required in order to make intelligent decisions that lower congestion in the LMA and as a result leads to better utilisation of the network. Given that the network supports multiple LMAs and that the agents' micro-mobility domains overlap, the proposed mechanism selects the LMA by distributing the incoming load optimally whilst maintaining the QoS requirements for the MNs.

Figure 5.1 depicts a typical scenario where, if there is no LMA selection, all the sessions will be routed through one LMA (e.g. LMA 1), hence congesting the mobility agent. This leads to certain paths being over-utilised, normally, paths around or nearby LMAs, while other paths remain under-utilised.

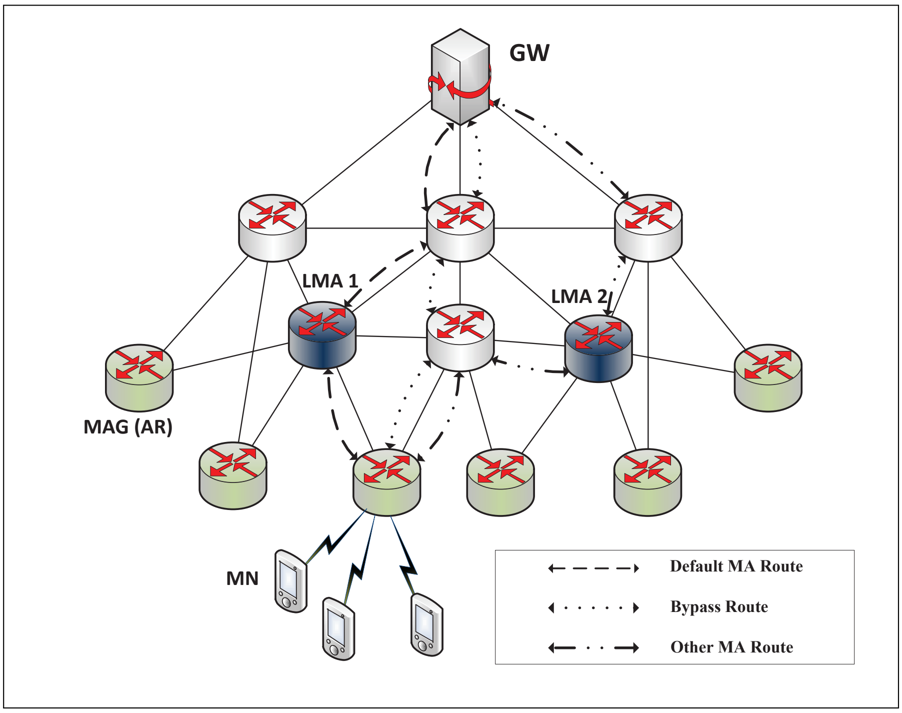


Fig. 5.1 Non-optimal routing in the presence of mobility agents (LMAs).

5.2 Proactive Load Uniformisation

In this section, we will present the fundamentals of PALU, our self-managed load balancing scheme.

5.2.1 Mobility Agent Selection Problem Description

This subsection describes the process of selecting the appropriate local mobility anchor based on the QoS requirements of new incoming sessions that is derived from [84]. The process, M-D-E cognitive cycle, is broken down into three stages.

Monitoring (M) Before the LMA selection mechanism takes place, the MAG obtains the network state characteristics which include network topology data such as the LMAs presence in the MAG domain and performance measurements such as the total capacity of the LMAs, the current utilisation/throughput of the LMAs, the distance from the LMAs to the MAG serving the MN, the MNs' mobility rate, and finally the MAG handover probability. These data are essential inputs to the LMA selection mechanism designed to find the best LMA that would accommodate the users QoS requirements as well as guarantee lower network congestion by optimally distributing the load across the lightly and heavily loaded LMAs.

Decision Making (D) For each LMA present in its network domain, the MAG will check against three constraint values. First the MAG checks which LMAs can support the required session throughput ensuring the LMA's capacity is not exceeded. Next, the MAG checks which LMA can support the average handover delay specified in the session request. For this parameter, the distance between the selected LMA and the MAG is considered. Finally, the packet delay requirement is taken into account. For this value both the LMA-MAG distance and LMA utilisation have to be considered. The farther away the LMA is from the mobile node, the larger the round trip time will be and, the higher the utilisation of an LMA is, the larger the packet delivery time will be.

Execution (E) If one or more of these three constraints is not met the MAG will switch to the next available LMA and repeat the process. If there is more than one LMA that meets the above criteria, the selection mechanism will choose the LMA with the least utilisation. Once the MAG selects the most optimal LMA, it assigns it to the mobile node enabling full local mobility support for that session.

5.2.2 Formal Model of PALU

In this subsection, the network model will be presented. Traditional Mobility Agent selection schemes aspire to allocate an MN to a MA and the MN utilises the MA until it moves away of its coverage region [85]. However, such schemes are static and can overload the MA leading to degradation of QoS of all the MNs served by that MA. In this chapter, a dynamic LMA selection mechanism for NetLMM framework is proposed for the purpose of balancing resources autonomously. We exploit the fact that the MAG provides the mobility services to the MN and each MAG can have association with multiple LMAs.

Network Model

A network is defined as a directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the node set (vertices) and $\mathcal{E}$ is the link set (edges) inter-connecting the nodes. Let $g \in \mathcal{V}$ denote the gateway router in the network, $\mathcal{I} \subset \mathcal{V}$ be the set of routers that serve as the LMA for mobile nodes, $\mathcal{M}$ the set of MAGs in the network such that $\mathcal{M} \subset \mathcal{V} - \{\mathcal{I}, g\}$ and $\mathcal{N} \subset \mathcal{V}$ the set of MNs. For a given MAG $m \in \mathcal{M}$, let $\mathcal{I}_m \subseteq \mathcal{I}$ be the set of LMAs that it can associate with and $\mathcal{N}_m \subseteq \mathcal{N}$ the set of Mobile Nodes attached to it. Note that $\mathcal{I}_m = \mathcal{I}$ if the MAG $m \in \mathcal{M}$ has connectivity to all of the LMAs and lies within the domain of all LMAs in the network. Also, note that $\mathcal{N}_m = \mathcal{N}$ if all the MNs are connected to MAG m. Each LMA serves a given number of MAGs within a network which is known as its domain. Finally, let $n \in \mathcal{N}_m$ be a mobile node attached to MAG $m \in \mathcal{M}$.

It is assumed that the network can support a set of traffic classes and provide appropriate QoS support (i.e. bandwidth guarantee). Service Level Requirements (SLRs) or QoS constraints for the sessions are associated with each class of traffic. The sessions are also identified according to their delay tolerance (delay sensitive or delay tolerant). Table 5.1 lists the different sessions supported by the network and their delay sensitivity along with the sessions required bandwidth. It also illustrates the corresponding symbols used for the study, where LP stands for Low Priority sessions, D stands for 'requests low delay', T stands for 'requests high throughput', and finally R stands for 'requests high reliability'.

Table 5.1 Traffic types with their respective QoS requirements and assigned symbols.

Traffic Class	Example	Delay Sensitive	Data Rate	Symbol
Class 1	VoIP	Yes	Low ($\approx$ 150Kbps)	(D + R)
Class 2	Video conferencing	Yes	High ($\approx$ 500Kbps)	(D + T)
Class 3	Real-time streaming	Yes	Medium ($\approx$ 250Kbps)	(D + R)
Class 4	Non real-time streaming	No	Medium ($\approx$ 250Kbps)	LP
Class 5	FTP	No	Medium ($\approx$ 200Kbps)	LP
Class 6	Web	No	Low ($\approx$ 100Kbps)	LP

Decision Making Process

When a new session request arrives at the MAG and is admitted to the network, the MAG obtains the QoS information for the session from a QoS agent such as a Bandwidth Broker (BB). We assume that the Type of Service (ToS)[86] or Differentiated Services (DiffServ)[19] will be used here. DiffServ uses the 6-bit

Differentiated Services Code Point (DSCP) field in the header of IP packets. The session is then check for its delay tolerant nature. On the one hand, if it is delay tolerant the session can bypass the LMA. On the other hand, if it is delay sensitive then the session is freed to use the LMA for local mobility support. In this case, the LMA selection mechanism will be carried out. Depending on the class of traffic, different QoS parameters will be considered first. Figure 5.2 depicts the state diagram of the decision making process at a MAG m. The mechanism is triggered upon arrival of a new session from the mobile user.

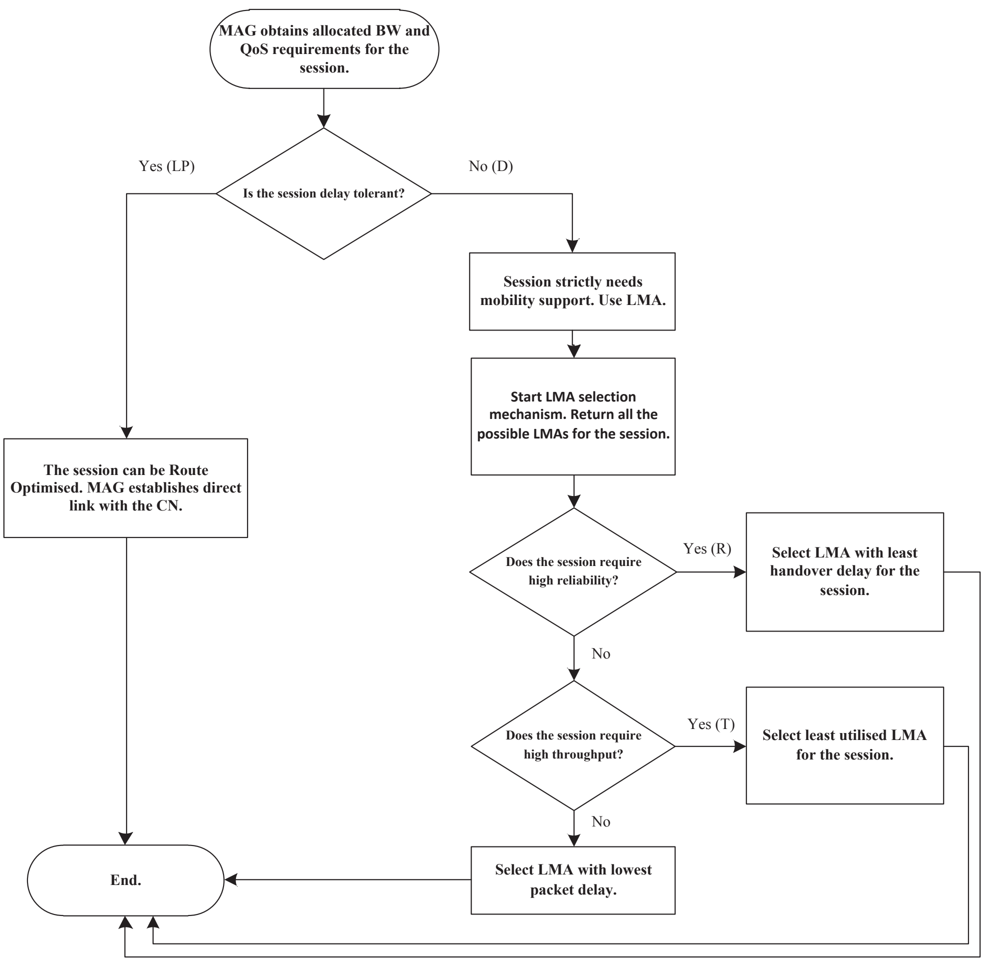


Fig. 5.2 State diagram of PALU's decision making process.

When a request for new MN or session with bandwidth ξ arrives at the MAG $m \in \mathcal{M}$, the MAG obtains the QoS information for the session by communicating with the QoS Agent. We define a binary integer variable

$$L_i = \begin{cases} 1, & \text{if LMA i is selected;} \\ 0, & \text{otherwise.} \end{cases}$$

and $ToS = [b_0 b_1 b_2 b_3 b_4 b_5]$, a 6-bit string corresponding to the ToS field in the IP header, with $\begin{cases} b_3 & = & \text{D} \\ b_4 & = & \text{T} \\ b_5 & = & \text{R} \end{cases}$ and $[b_0 b_1 b_2]$ represent the IP Precedence bits and define the priority or importance of an IP packet. For example, Precedence 0 ($[b_0 b_1 b_2] = [0\ 0\ 0]$) refers to "Routine".

D, T and R are also binary integer variables defined as follows:

$$D = \begin{cases} 1, & \text{if session requests low delay;} \\ 0, & \text{otherwise.} \end{cases}$$

$$T = \begin{cases} 1, & \text{if session requests high throughput;} \\ 0, & \text{otherwise.} \end{cases}$$

And, $R = \begin{cases} 1, & \text{if session requests high reliability;} \\ 0, & \text{otherwise.} \end{cases}$

If the session is delay tolerant, then the session flow will bypass the LMAs and directly register with the Correspondent Node (CN) taking the shortest path from the MAG to the gateway. If the session is delay sensitive (i.e. it strictly requires mobility support by the use of an LMA), then the LMA selection mechanism starts. The process will select every LMA $i \in \mathcal{I}_m$, one after the other, and will obtain the LMA related network state information, namely the total capacity of the LMA, its current utilisation, the distance from the MAG m to LMA (number of hops) and MAG handover probability. The procedure then checks the ToS bits (D, T and R) and selects the appropriate LMA for the MN accordingly.

Upon looking at the ToS bits, the MAG chooses which LMA to associate with the mobile node. There are three possible outcomes:

- If $[D\ T\ R] = [1\ 0\ 1]$, then the session requests high reliability; the MAG will select the LMA that ensures the lowest average handover delay experienced by the MN if it selects this LMA
- If $[D\ T\ R] = [1\ 1\ 1]$, the session request high throughput; the MAG will associate with the MN the LMA which is the least utilised
- If $[D\ T\ R] = [1\ 0\ 0]$, the session is only delay sensitive; the MAG will then choose the LMA that ensures the lowest average packet delay experienced by the current mobile node

By knowing the D, T and R bits, the decision making described in Algorithm 2 is executed. For the downlink traffic, the same decision making and routing policy is applicable by interchanging the direction of packet from gateway to MAG. H^i, L_i and T_i are respectively the average handover delay experienced by the MN if LMA $i \in \mathcal{I}_m$ is selected, the load of the LMA i and the average packet delay experienced by the MN if it selects the LMA i. T_s, H^n and C_i are respectively the QoS required packet delivery time, the accepted handover delay and the capacity of the LMA $i \in \mathcal{I}_m$. We denote by $\bar{P}$ the set of paths in the network that do not reside in the paths of each of the LMAs in the network.

Objective Function of Load Uniformisation

For each of the LMA $i \in \mathcal{I}$, we note C_i its raw capacity in terms of the maximum allocated resource, in bps, that the LMA can handle. A traffic flow coming from or to a mobile node $n \in \mathcal{N}_m$ attached to MAG $m \in \mathcal{M}$ through an LMA $i \in \mathcal{I}_m$, is given as x^n_{mi}. Hence, we define U_i as the utilisation of an

Algorithm 2 Decision Making Process

procedure DECISION-MAKING($\bar{\mathrm{P}}$, $\mathcal{I}$, $\mathcal{M}$, $\mathcal{V}$)
  if Packet arrives at MAG $m \in \mathcal{M}$ destined to gateway $g \in \mathcal{V}$ with $D = 0$ **then**
    Calculate least cost path from MAG m to gateway g from $\bar{\mathrm{P}}$
    Route packet along this path to gateway g
  else if Packet arrives at MAG $m \in \mathcal{M}$ destined to gateway g with $D = 1$ **then**
    Find LMAs s.t.

$$\sum_{i \in \mathcal{I}_m} L_i = 1, \quad \forall i \in \mathcal{I}_m \tag{5.1}$$

$$L_i \in \{0,\ 1\}, \quad \forall i \in \mathcal{I}_m \tag{5.2}$$

$$T_i.L_i \leq T_s, \quad \forall i \in \mathcal{I}_m \tag{5.3}$$

$$H^i.L_i \leq H_n, \quad \forall i \in \mathcal{I}_m \tag{5.4}$$

$$x^n_{mi}.L_i = \xi, \quad \forall i \in \mathcal{I}_m \tag{5.5}$$

$$\Big(\sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{I}_m} x^n_{mi}\Big).L_i \leq C_i, \quad \forall i \in \mathcal{I}_m \tag{5.6}$$

    if $R = 1$ **then**
      Select LMA $i \in \mathcal{I}_m$ s.t. $H^* = min_{\forall i \in \mathcal{I}_m}\{H^i\}$
      start FUNCTION ROUTING
      Calculate least cost path from MAG $m \in \mathcal{M}$ to LMA i.
      Tunnel the packet through this path to LMA i.
      When packet reaches LMA i, calculate least cost path to gateway g.
      Route packet along this path to gateway g.
      end FUNCTION ROUTING
    else if $T = 1$ **then**
      Select LMA $i \in \mathcal{I}_m$ s.t. $U^* = min_{\forall i \in \mathcal{I}_m}\{U_i\}$
      Do FUNCTION ROUTING
    else if $(R = 0)$ AND $(T = 0)$ **then**
      Select LMA $i \in \mathcal{I}_m$ s.t. $T^* = min_{\forall i \in \mathcal{I}_m}\{T_i\}$
      Do FUNCTION ROUTING
    end if
  end if
end procedure

LMA i as follows:

$$U_i = \frac{\sum_{m \in \mathcal{M}} x_{mi}}{C_i} \tag{5.7}$$

Where x_{mi} represents the total flow of all mobile nodes in an MAG using the LMA i,

$$x_{mi} = \sum_{n \in \mathcal{N}_m} x_{mi}^n \tag{5.8}$$

Similarly, one can define,

$$x_m = \sum_{i \in \mathcal{I}_m} x_{mi}, \ \forall m \in \mathcal{M} \tag{5.9}$$

as the total flow at an MAG $m \in \mathcal{M}$.

At any instance of time, given that a mobile node n requests for a session of flow x_{mi}^n at the MAG m, the MAG m can select the best LMA for an incoming mobile node's session from the available set of LMAs ($\mathcal{I}_m$) by distributing the load optimally according to the following load function.

$$U_i = \frac{\sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}_m} x_{mi}^n}{C_i}, \quad \forall i \in \mathcal{I}_m \tag{5.10}$$

By the limits of capacity for a given LMA the value of L_i ranges from $[0, 1]$. To penalise the LMAs that are highly utilised compared to the underutilised LMAs we define an objective function based on the load function. This objective function by distributing the LMA load uniformly reduces the load from the highly utilised LMAs and shifts it to the least utilised LMAs instead. Let the least utilised LMA in the network be given by,

$$U^* = min_{\forall i \in \mathcal{I}} \{U_i\} \tag{5.11}$$

Hence the objective function to distribute the LMA load uniformly is given as,

$$\sum_{i \in \mathcal{I}} \exp\{\alpha(U_i - U^*)\}, \tag{5.12}$$

where $\alpha \geq 1$ is a scaling constant.

The cost is determined by the output of the objective function. Moreover, the objective function is in an exponential form. The higher the network load will be, the smaller the difference between the selected LMA i (any LMA) and the least utilised LMA, calculated at each MAG $m \in \mathcal{M}$ as follows:

$$\text{Min} \quad \sum_{i \in \mathcal{I}_m} \exp\{\alpha(U_i - U^*)\}, \tag{5.13}$$

$$\tag{5.14}$$

$s.t.$ (5.1), (5.2), (5.3), (5.4), (5.5) and (5.6).

5.3 Simulation Setup

This section describes the simulation modelling and the MAG routing operations used to obtain the results presented in Section 5.4.

5.3.1 Simulation Modelling

Figure 5.3 shows the chosen topology used for the simulation. Note that the simulations were carried out using Network Simulator 2 (NS2) software. The topology reppresents an Internet domain with a single gateway towards the big Internet. It is assumed that the access network connects a certain number of equipments aggregating end users with different access technologies such as WiFi, radio, ADSL, FTTH running various applications. The backbone network is constituted of a hierarchy of nodes connected by wired Ethernet links forming a partial mesh topology. Outside the domain simple nodes emulate core domains, home agents and correspondent nodes; to connect to the outside the domain uses multiple border routers, namely Access Network Gateways (ANGs).

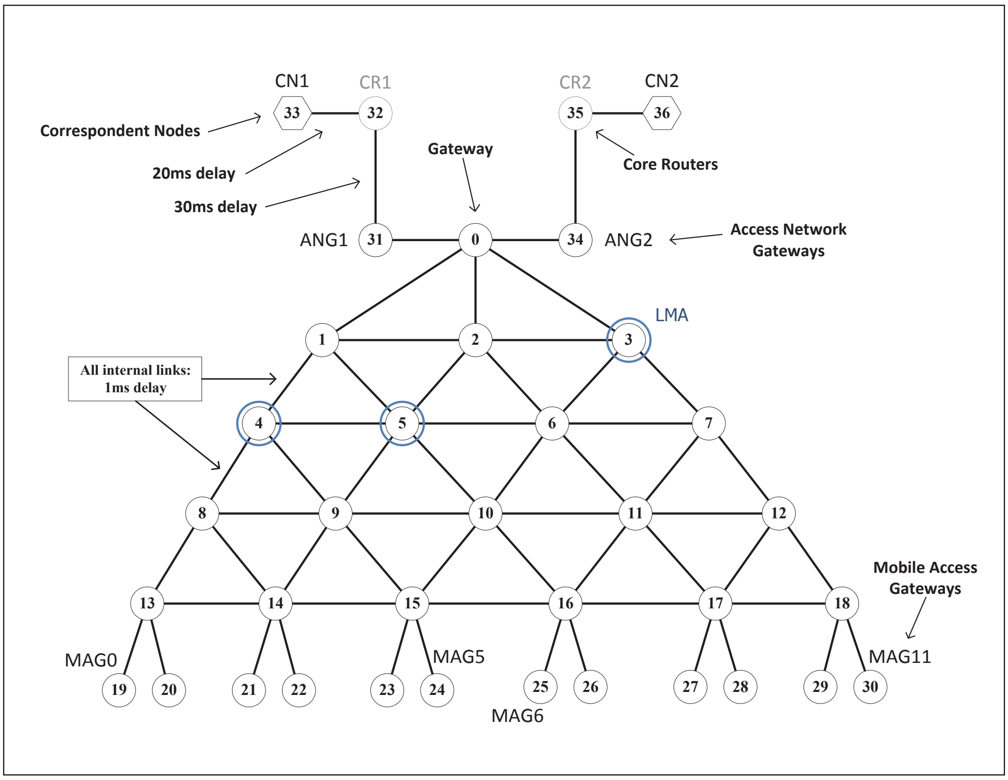


Fig. 5.3 Reference topology.

The topology features three LMAs (number $3, 4$ and 5, see Figure 5.3), whose location has been arbitrarily chosen (more details on location and number of LMAs in [87]). Also, twelve base stations (BSs) [number $19 - 30$] that share the capabilities of MAGs, i.e. they are considered as intelligent routers in which the LMA selection algorithm is implemented. The MAGs are interconnected to the single gateway by a series of standard routers [numbered $1 - 18$] and organised in a hierarchical tree-like structure of point-to-point wired links of 100 Mbit/s, apart from the links connecting the GW which are of 1 Gbps, so that these links will not create congestion around the GW. The gateway in this case is the tree root of the access network through which traffic is flowing to reach the Internet (and HA). It is used to centralise the management functions, while presenting to the Internet the domain as a classical IP network. All internal links feature the same constant delay of 1 ms. The simulated backbone links can be customised by introducing link failures and/or link load, which are used to test the robustness of the mechanism. Also, the network uses $M/M/1$ queues in each node.

5.3.2 MAG Routing Operations

This section describes how the routing is carried out in the MAG. This stage is initiated once the decision making is complete and the LMA selection mechanism has selected the LMA to be used for a specific session. We suppose that NetLMM protocol allows a MAG to utilise more than one LMA. This is done by enabling the MAG to perform multiple registrations on behalf of the MN. As a result, the MAG will be able to configure a globally reachable address from each additional LMA it registers with and use this address to communicate with the outside world on behalf of the MN. We call this address the Proxy Home Address (P-HoA). The solution is based on a Network Address Translation (NAT) scheme as well as a new binding cache table used to map each additional P-HoA to the MN default/home address. The network address table is the heart of the forwarding entries operation which takes place within the MAG as packets arrive and leave its interfaces. A routing example of three sessions is illustrated in Figure 5.4.

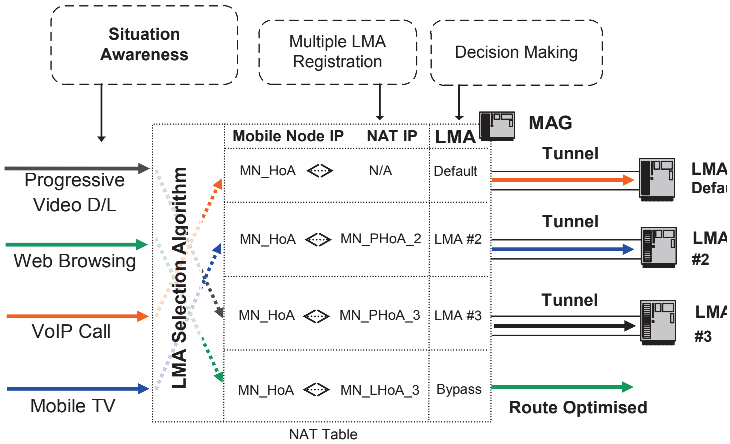


Fig. 5.4 An example of routing based on the local LMA selection mechanism.

5.4 Performance Evaluation

This section presents the performance evaluation of PALU strategy. The objective of this mechanism is to select the most appropriate local mobility anchor by distributing the incoming load optimally whilst taking into account and maintaining the QoS requirements of the mobile nodes. Therefore, the performance results will focus on both the network operator as well as the performance of the network as perceived from the user point of view. In the context of network operators the LMA selection mechanism is evaluated in terms of bandwidth utilisation and compared against a network that does not use this mechanism.

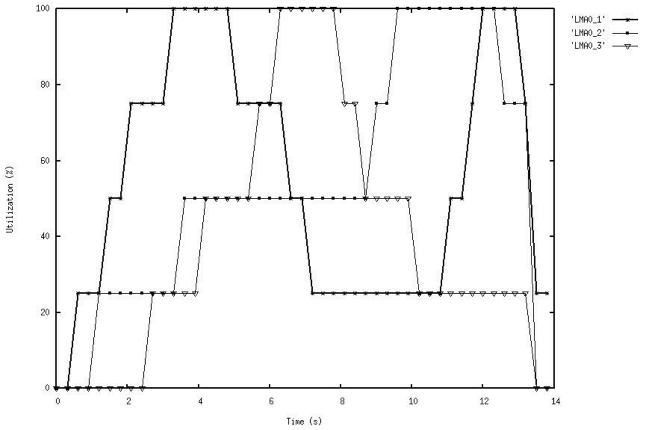
In the context of the user the selection mechanism is evaluated in terms of user experience. User experience is becoming the ultimate measure of how subscribers perceive the performance of the network and its services. Using the network simulator the closest we can get to measuring user experience is focused on measurements of TCP flows such as flow sequence number, packet loss and congestion window. These parameters will have a direct impact on the user experience. This section presents the results of the simulation based on the scenario described in the section above.

5.4.1 LMA Selection Mechanism Inactive

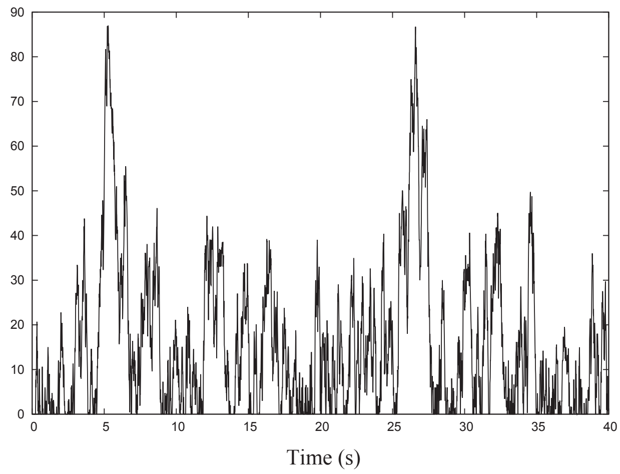
In order to monitor the performance of our strategy, we decide to use a TCP session that is running throughout the simulation, we named it 'TCP0'. Figure 5.5 depicts three routing metrics used to evaluate the performance of the mechanism. Figure 5.5(a)shows the utilisation of the three LMAs when the simulation is run without the presence of the LMA selection mechanism. This also forms the benchmark by which the LMA selection mechanism will be assessed in terms of its performance. Figure 5.5(b) indicates the queue size (in packets) of one of the LMAs, namely LMA 1, in the same case and finally Figure 5.5(c) represents the averaged throughput of TCP0 (in bits).

The simulation begins at $t = 0s$ with the first TCP flow starting half a second later in MAG 0 and being routed through LMA 1. LMA 1 is the first one to reach 75% utilisation at $t = 2s$. When the LMA is congested, packets are dropped. The first such congestion takes place at $t = 3s$. As more traffic flows are generated two further congestions occur; one at LMA 3, $t = 6s$, and the other one at $t = 12s$ when two LMAs are congested.

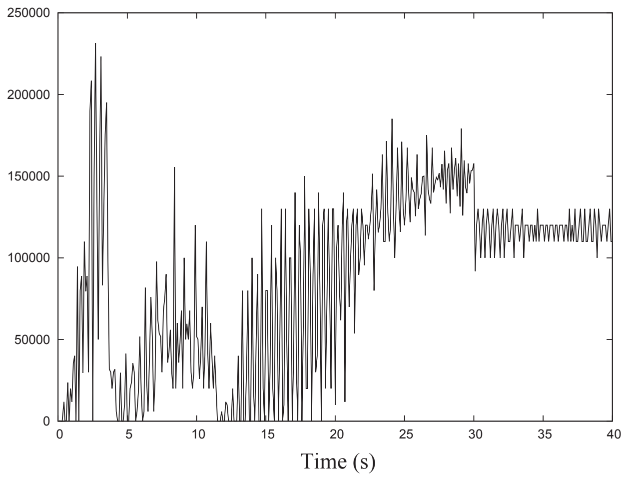
When the selection mechanism is not in use the MAGs allocate each new session to the LMA closest to them or within their domain. Queue size of LMA 1 presents two peak values and an average value of 34 packets. When congestion at LMA 1 is reached, the queue at the LMA fills up to full buffer size, set to 90 packets in the simulations (see Figure 5.5(b)). From Figure 5.5(c), it can clearly be seen that TCP0 enters the "slow-start" phase, part of the congestion control strategy used by TCP protocol, which designates congestion. After detection of congestion (acknowledgment not received due to packet loss), TCP enters the linear growth (congestion avoidance) phase. As shown in Figure 5.5 this leads to non optimal routing and causes congestion in some LMAs while other LMAs remain under-utilised. The simulation was repeated with the LMA



(a) LMA utilisation(%)



(b) Queue size of LMA1



(c) Average throughput of TCP0

Fig. 5.5 Selection Mechanism Inactive.

selection mechanism turned on. In order to compare the two simulations the same scenario generation process was used.

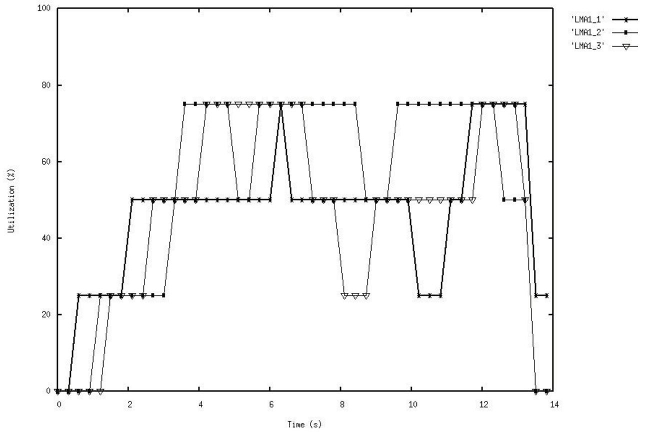
5.4.2 LMA Selection Mechanism Active

The results, with the LMA selection mechanism in use, are shown in Figure 5.6. With the LMA selection active the MAGs are able to make intelligent decisions that lead to better utilisation of the network resources. Figure 5.6(a) shows that each incoming session is allocated to an LMA by distributing the incoming load uniformly. As a result the LMAs do not get congested while the maximum utilisation of each LMA remains at 75%.

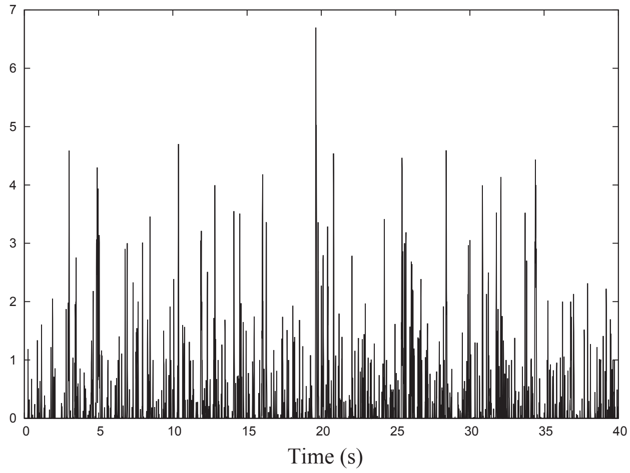
In Figure 5.6(b), it can clearly be seen that the queue size counts less elements with the selection mechanism on, hence this leads to minor or even no queueing delays at the mobility agents, and therefore lessened end-to-end delays. Indeed, the average number of packets in the queue of LMA 1 is 2.1 compared to 34 packets when selection mechanism is inactive. Finally, from Figure 5.6(c), it can be drawn that TCP throughput remains at its fullest, which is not the case when the selection mechanism is inactive as in Figure 5.5(c). Received throughput of TCP0 reaches a value of 250 Mbps, whereas it reached 120 Mbps with selection mechanism turned off.

5.4.3 Impact of PALU on the traffic

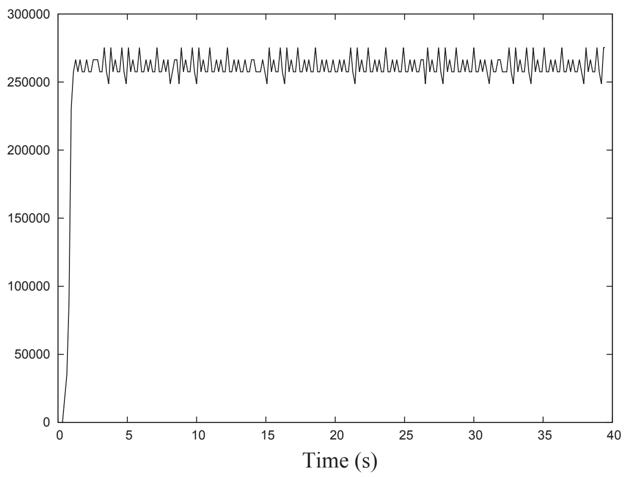
When making a decision the LMA selection mechanism also takes into account the QoS requirements of the incoming session. These are parameters that control the priority, reliability and quality of that session. By considering these parameters in the selection process, the LMA selection mechanism is able to offer the user the QoS that was requested, having a direct impact on how users perceive the performance of the network and its services. For



(a) LMA utilisation(%)



(b) Queue size of LMA1



(c) Average throughput of TCP0

Fig. 5.6 Selection Mechanism Active.

example, a network with a good user experience will achieve customer loyalty and maintain a competitive edge. On the other hand, a poor user experience may result in dissatisfied customers leading to a poor market perception and ultimately brand dilution. One way of capturing the user experience from the network simulations is to focus on Key Performance Indicators (KPIs) such as TCP sequence number, packet loss and congestion window. These are the KPIs that will have a direct impact on the session quality experienced by the user. In order to monitor how a user session is affected we focus on one LMA in the network and set up a TCP flow to run through this LMA during the entire duration of the simulation. We then monitor this flow with the selection mechanism inactive and compare the results when the selection mechanism is active. Recall that at the start of the simulation a TCP flow is initiated labelled TCP0. This flow is monitored throughout the simulation and is shown in Figure 5.7 and Figure 5.8, where "SMI" stands for "Selection Mechanism Inactive" and therefore "SMA" stands for "Selection Mechanism Active"

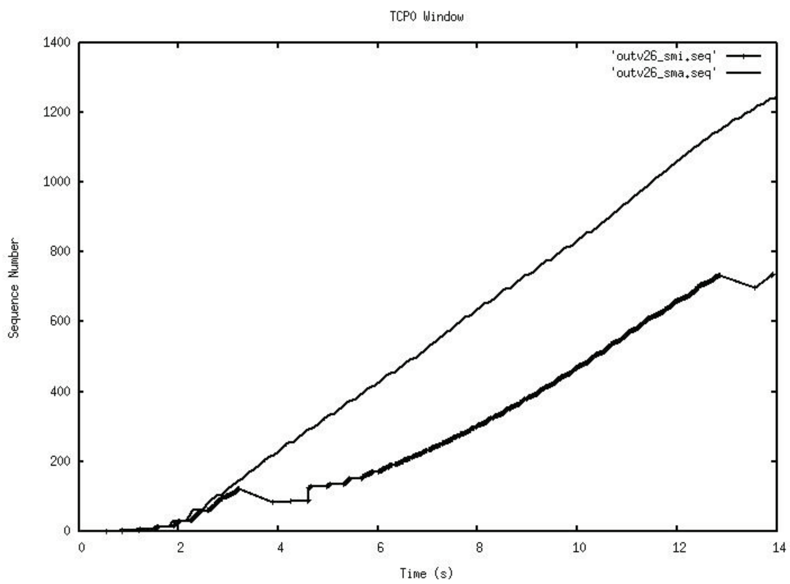


Fig. 5.7 TCP sequence number.

By monitoring the sequence number of a TCP connection we can identify packet loss, among other issues, that may occur during transmission. Figure 5.7 shows that when the selection mechanism is inactive there is significant packet loss at $t = 3s$ and $t = 13s$. Packet loss directly affects the user experience in different ways. For a TCP connection packet loss will initiate the slow-start mechanism (which is part of the congestion control used by TCP). This effect is captured and shown in Figure 5.8. The TCP connection enters the congestion avoidance phase by reducing the congestion window size by half and resuming with linear growth. From the user point of view, this packet loss will impact the TCP throughput resulting in higher download times and negative user experience.

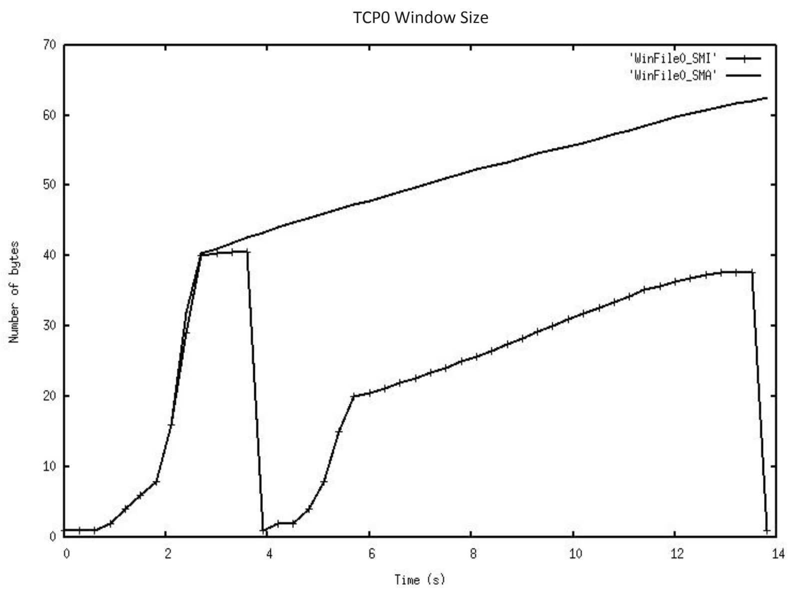


Fig. 5.8 TCP window size.

Furthermore, the frequency as well as the packet loss distribution (measure of the packet loss distribution across the timeline) is also very important. For example, a high distribution percentage loss means that all the lost packets are in a small window of time causing a bigger quality issue to the user. The same figures show and compare the results obtained when the LMA selection mechanism is used. It is clear that the performance, when the LMA selection mechanism is active, yields a far better user experience with no packets lost and no reduction in throughput during the duration of the simulation. This example illustrates the benefits of the LMA selection mechanism not only to the network operator (e.g. reducing network congestion) but also in providing and maintaining the QoS requirement of the users.

5.5 Concluding Remarks

In this chapter we presented PALU, an agent based micro-mobility solution, integrating cognitive behaviour in network elements (MAGs) for the purpose of unskewing network utilisation. Also, the importance of optimal mobility agent selection was investigated. It was shown that the presence of mobility agents (LMAs) leads to tunnelling overheads and extra processing load at LMAs. As a result all traffic is forced to flow through the local mobility anchors; over-utilising paths along the local mobility anchors while other paths of the network remain under-utilised. Such effects can have adverse impact on the network causing undesired network performances.

This chapter provided a solution to lower the network congestion caused by the LMAs by distributing the incoming load uniformly across the LMAs while lowering the packet loss rate and increasing session throughput. It is assumed that the MAG could retrieve QoS information for incoming flows by examining Layer 3 parameters such as DSCP or the application signature as provided by Cisco's Network Based Application Recognition (NBAR) technology [70]. We also exploit the fact that not all sessions require the use of LMAs. Some flows (such as email and web traffic) can bypass the LMAs thus further lowering the network congestion. Therefore, the analysis was focused on the integration of the variant of the M-D-E generic cognitive cycle, presented in 5.2.1, with the standard protocol operations.

In addition, when a small number of LMAs is deployed, the congestion of all LMAs is inevitable. These LMAs will eventually get congested thus not being effective. For future work, it would be of interest to consider combining the LMA selection mechanism with a mobility agent deployment scheme that would determine the optimal number and location of the local mobility anchors so that the network is balanced and congestion is avoided.

Chapter 6

Conclusions and Future Work

6.1 Concluding Remarks

In this dissertation, we have proposed a novel routing mechanism that provides QoS traffic engineering and provisioning in future access networks. The problem has been studied in two different scenarios. First, we have addressed the problem in all-IP metro access networks where edge nodes can make full use of network path diversity to balance traffic load whilst finding optimal path that respects the service level agreements for the session. Second, for a case where the network is a mobile access network and uses a network-based localised mobility management solution (PMIPv6). The main objective has been to not only provide an implementable and efficient QoS-aware routing of flows, with the objective of minimising network congestion by using the network's available links, but also tackle the inefficiency of mobility agent selection and load balancing in access networks that provide mobility support. The mechanisms proposed are independent from each other as there are applicable in different scenarios but contribute toward the same goal: how can routing be optimised for traffic engineering while satisfying the service level requirements for each flow? Of the two, the first proposed technique, a novel QoS-aware routing, based on the multi-topology routing approach, Multi-Plane Routing (MPR), has been introduced. The presented approach aims to minimise the cost, in terms of the load on each link, with respect to how to make full use of the network resources, hence avoiding skewing the network utilisation. To that end, heuristic algorithms have been designed to extract high path diverse logical views of a network, i.e. routing planes, while keeping their number to a minimum, typically 3-5, to minimise protocol overhead; this offline traffic engineering is part of the network planning phase. Subsequently, the routing planes, effectively the different link weight configurations, are fed into the network, and the edge routers then start the flooding process of link state information. Upon incoming flows, the traffic is routed in compliance with the negotiated SLA. The proposed scheme applies multiple constraints on the planes for an incoming flow, and then selects the optimal routing plane that will be used for forwarding the flow's packets across the network. To investigate the performance of the new scheme, the optimisation framework has been presented, aiming to minimise the congestion cost of the network subject to defined constraints. The results obtained showed that the efficient resource utilisation, even under unpredictable traffic spikes, an be ensured while at the same time, the traffic needs can be fulfilled by the selected path.

Second, a new load balancing technique for agent micro-mobility protocol based access networks has been investigated. As the presence of Mobility Agents (MAs) in these networks can lead to constrained routing and create areas of bottleneck around them, an optimal and robust mobility agent selection is required. Proactive Load Uniformisation (PALU), our self-managed load balancing scheme reduces the congestiong caused by MAs leading to better utilisation of the network resources. Assuming that the network supports multiple MAs, the proposed solution selects the optimal MAs by distributing optimally the incoming load within the network whilst at the same time maintaining the QoS requirements for the mobile nodes.

In addition to the main contributions discussed above, this research work has provided the following complementary contributions: the performance of the proposed schemes has been thoroughly investigated by means of the developed analytical framework, and the network-level simulation scenario conducted in NS-2. Especially, we have built an entire NS-2 module for enabling MPR on top of the current link-state module present in NS-2. To that end, we have created a patch for NS-2 that is available on a per request basis, this is described in Appendix B. Secondly, the applicability of the proposed scheme to the existing QoS, routing and mobility management protocols in the similar context was investigated. Several metrics, such as the network overall throughput, flow latency, blocking probability were thoroughly studied.

6.2 Future Avenues of Research

In this section, we would like to open the following interesting issues, that among many others, can be continued as the future research.

- **Real-world Application**

  Using real network trace data from metro access networks (e.g. Metronet UK) would be very valuable so that we could evaluate and validate the performance of our Multi-Plane Routing approach. A real-world 5G-like network testbed would also allow to quantify the processing overhead caused by MPR on edge-routers and compare it with an identical setup where MPLS is used.

- **Random Graph Model for MPR**

  Following the footsteps of Paul Erdős and Alfréd Rényi who first introduced one of the most famous random graph model, sculpting the network to enable the full potential of our novel Multi-Plane Routing strategy and assessing its performance in a real-world scenario, is a very interesting research topic.

- **Traffic Optimisation in Mobile IP Networks**

  The deluge of bandwidth-starving applications for mobile users, peaking during the daily commute with 70% usage [88], as well as the upcoming changes in users' traffic types, has opened up a whole new area of challenges for access networks. It has been estimated that these changes will lead to the 10-fold increase in the global mobile data traffic between 2014 and 2019. While mobile video traffic exceeded 50% of total traffic for the first time in 2012, it is expected to increase 13-fold between 2014 and 2019 [89]. It is believed that the use of QoS-aware traffic optimisation, in the contect of the mobility in IP networks, is a new area with a great scope of innovation. Therefore, applying the optimisation ideas introduced in this thesis to mobile networks, wherein there are areas of congestion, created due to the presence of the local mobility agents, can yield interesting insights.

- **Green Networking**

  In UK, ICT equipment accounts for roughly 10% of their total energy consumption [90]. In order to reduce the CO2 emissions, energy saving has become paramount in designing the next generation networks. Shutting down the network devices carrying light loads and redirecting the traffic flows to other routes, using Multi-Plane Routing, would be a way to decrease network energy consumption. We believe this is a very important and interesting research issue, worthy of investigation.

- **MPR and SDN**

  Software-Defined Networking (SDN) breaks vertical integration, separating network's control logic form the underlying routers and switches, promoting logical centralisation of network control and introducing the ability to program the network. Furthermore, implementation network functions in software would reduce the overhead incurred by MPR.

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Appendix A

List of Publications

The list of publications related to the contributions of the thesis are as follows:

- Alexandre Jaron, Andrej Mihailovic and Hamid Aghvami. QoS-Aware Multi-Plane Routing Method For OSPF-based IP Access Networks. Submitted to Elsevier Computer Networks Journal (Resubmitted after minor corrections)
- Andrej Mihailovic, Apostolos Kousaridas, Alexandre Jaron, Paul Pangalos, Nancy Alonistioti and Hamid Aghvami. Self-Management for Access Points Coverage Optimization and Mobility Agents Configuration in Future Access Networks. Springer Wireless Personal Communications Journal, September 2013.
- Alexandre Jaron, Mathieu Danel, Paul Faucheux, Andrej Mihailovic and Hamid Aghvami. QoS-Aware Multi-Plane Routing for Future IP-based Access Networks. Global Communications Conference (GLOBECOM), December 2012.
- Alexandre Jaron, Andrej Mihailovic, Paul Pangalos and Hamid Aghvami. Proactive Autonomic Load Uniformisation with Mobility Management for Wireless IP Access Networks. IET Networks Journal, December 2012.

- Alexandre Jaron, Andrej Mihailovic and Hamid Aghvami. Introducing Multi-Plane Routing for Next-Generation All-IP Wireless Access Networks. International Conference on Communications (ICC), June 2012.

- Alexandre Jaron, Paul Faucheux, Mathieu Danel, Andrej Mihailovic and Hamid Aghvami. Implementing extensions to IP routing for increasing throughput in Future Internet. Wireless World Research Forum (WWRF) Meeting 28, April 2012.

- Alexandre Jaron, Paul Pangalos and Hamid Agvami. How can Multi-Plane Routing be used as a Routing Paradigm in Future IP-based Wireless Access Networks? Wireless World Research Forum (WWRF) Meeting 27, October 2011.

- Dev Pragad, Alexandre Jaron, Paul Pangalos and Hamid Agvami. Dynamic Mobility Anchor Selection Mechanism with QoS Constraints. IEEE Communications Letters, 2011.

Appendix B

Extension to NS-2: MPR Module

In this appendix, we will describe the extensions made to network simulator NS-2 to enable our Multi-Plane Routing scheme, as well as the simulation details used for the performance analysis of our method. Please note that we have created a patch that can be simply applied to the NS-2 Version 2.35. This appendix is organised as follows: Section B.1 will present the details of the implementation, i.e. the additions made to the routing tables and node agents. Finally, the traffic generator module will be depicted in Section B.2

B.1 Details of the Implementation

In order to integrate MPR into NS-2, MT-OSPF needed to be implemented, therefore not only the core of the simulator needed upgrading, but also additional modules to extend the link-state routing protocol needed to be built.

B.1.1 Routing Table and Link-State Messages

The core concept of MPR is to emulate one instance of OSPF for each plane, hence another dimension needed to be added to the Topology database, see Figure 3.1 in Chapter 3. In the standard OSPF protocol, each link is associated with a link weight/cost. This cost is then used to compute the shortest paths using Djikstra's algorithm. In OSPF, link-state advertisement (LSA) messages contain only one integer for link weights. Instead of an integer, we have implemented an array of integers allowing independent link weights, see Figure B.1 for the MT-OSPF router LSA we have implemented: We then modified the flooding process in order not to have one flooding per plane but one global flooding that contains information for all the routing planes. This ensures minimum signalling overhead. The flooding consists of the initial stage upon building routing tables. It is the process of getting the link-state advertisements to every router.

B.1.2 Node configuration

The second main modification that we made to the core of NS-2 link-state protocol is for each node to understand the separate independent link weights corresponding to each plane. An architectural view of then enhance NS-2 node is depicted in Figure B.2. In NS-2, a node is mainly constituted of a set of classifiers and agent objects. There is one agent per flow in the source node and in the destination node. An agent represents several layers of the protocol stack, it defines primarily the UDP or TCP protocol. Classifiers route packet depending on the destination node (*DestClassifier*), their agent (*PortClassifier*) and their flow ID, FID *FIDClassifier* toward a slot. In every valid slot, there is another NS object connected.

In the MPR-enabled node, an incoming packet is first sorted by its FID. In our

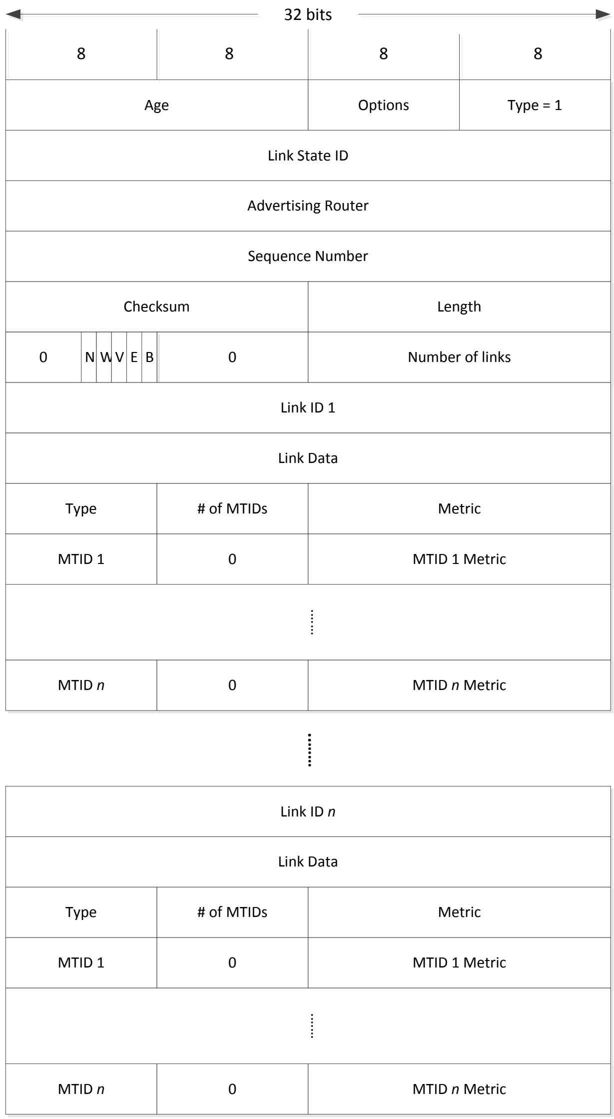

Fig. B.1 MT-OSPF Router LSA.

case, the FID represents the routing plane. On each slot of the *FIDClassifier*, there is a *DestClassifier* that represents the FIB (i.e. routing table) previously computed. If the packet is sent to the current node, then it is routed toward the *PortClassifier* where its receiving agent is connected. Otherwise, it is routed toward the next hop. In NS-2, source agents are connected to the entry of the node. In our case, the FID of a flow is set to the plane it belongs to. Hence,

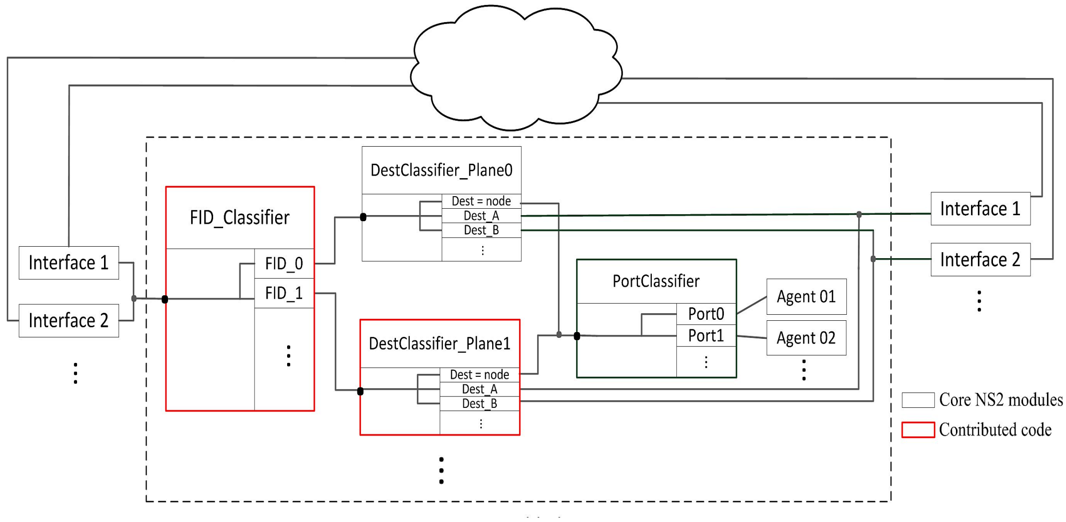

Fig. B.2 MPR-enabled Node.

new packets will go from their agent through the *FIDClassifier* of their source node and will be routed using the *DestClassifier* of their plane.

B.2 Traffic Generator

As part of the extension to the link-state NS-2 module, we have also created a traffic generator, responsible for generating flows of packets of different rates, with different life-times, and at random intervals. Two functions were built for this purpose (see Figure B.3). *genTraffic* this function generates a new flow. The flow will belong to a randomly chosen class (VoIP, streaming video, browsing, etc.). Each class is associated with its own characteristics of duration, data rate and QoS requirements. A destination node is randomly chosen in the destination list.

stopNewTraffic this function is called to stop a flow. This function programs the next start of the flow. In our scenarios, the aim was to increase the traffic linearly to eventually overload the network. With this strategy, the network becomes more and more loaded with traffic, because the number of new flows grows steadily whil the older flows continue to run. There is a "pause" between the time a flow stops and it starts again in order to first simulate bursty traffic, and second allow new flows to potentially run even when the network is overloaded.

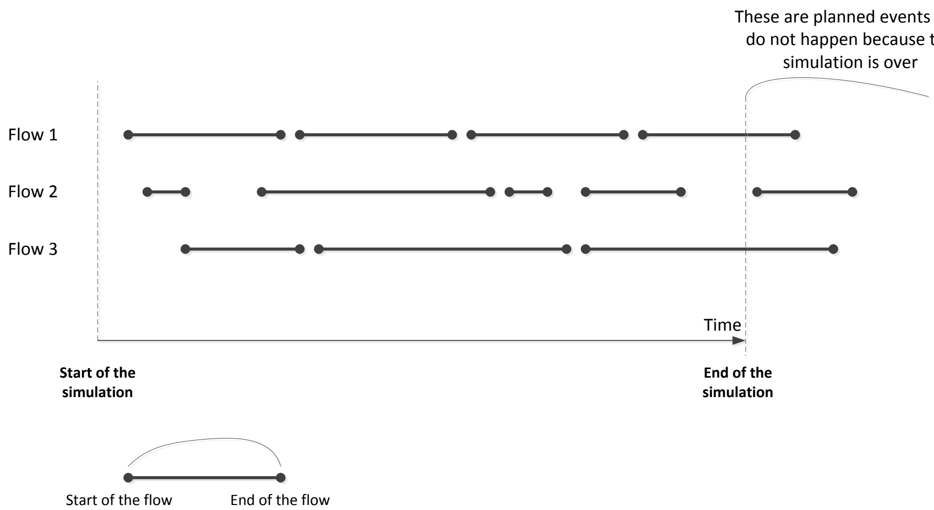

Fig. B.3 Example of the traffic generator's output.

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